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(71) Applicant: **NORTHERN TELECOM LIMITED**  
**Montreal, Quebec H2Y 3Y4 (CA)**

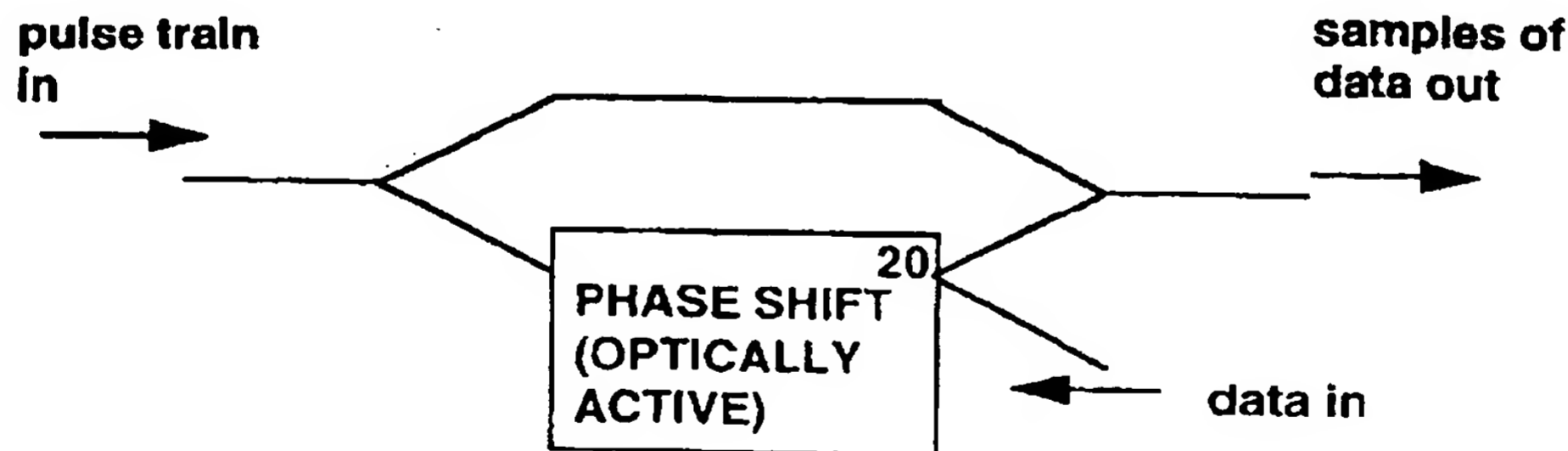
(72) Inventors:  
• **Roberts, Kim Byron**  
**Welwyn Garden City, Herts AL8 7DL (GB)**  
• **Hadjifotiou, Anagnostis**  
**Harlow, Essex CM19 4RD (GB)**

(74) Representative: **Ryan, John Peter William et al**  
**Nortel Patents,**  
**London Road**  
**Harlow, Essex CM17 9NA (GB)**

(54) **All-optical sampling by modulating a pulse train**

(57) An interferometer, such as a Mach-Zehnder type is fed with a pulse train. One arm is fed with a data stream, so as to modulate the pulse train according to the data stream. This enables the data stream to be re-generated, or sampled without converting from optical

form into electrical form. Thus all optical regeneration, multiplexing, demultiplexing or retiming to remove jitter, can be achieved. An optical amplifier (20) in one arm of the interferometer enables the interference condition of the interferometer to be varied, to cause the pulse train to be modulated by the data.



**Fig 3**  
**INTERFEROMETER ARRANGEMENT**

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## Description

### Field of the Invention

The invention relates to methods of modulating a pulse train, methods of using an interferometer, interferometers having a control input, and optical samplers, and optical pulse reshaping arrangements.

### Background to the Invention

At any stage in an optical path in, for example, an optical transmission system for an optical computing system, pulses used to transmit data may become distorted. It is most important that the information can be recovered from the optical signal at a receiver, or that the signal can be reconstructed at a repeater, for onward transmission. As bit rates increase, the expense and complexity of receiver and regeneration (or repeater) hardware rises considerably.

For retiming of optical pulses for multiplexing or regeneration, the basic requirement is for a device which will sample the signal accurately.

It is known to do this electrically at lower speeds, and various attempts have been made to do this optically at higher speeds. For example, a decision gate for all optical data retiming, operating at 1 Gbit/s is known from Electronics Letters 7 January 1993, volume 29, no. 1 "Decision Gate for all Optical Data Retiming Using a Semiconductor Laser Amplifier in a Loop Mirror Configuration", Eiselt et al. A loop interferometer is fed with the raw data signal and a clean clock signal. The clock pulses are modulated by the data using a semiconductor laser amplifier in the loop. This shifts the phase of the clock signal, when data is present, so as to cause constructive or destructive interference. Thus the clock signal can be output with its amplitude modulated by the data. This effectively means that the modulated clock can be regarded as a regenerated, retimed data signal. The document discusses the application of this technique in an all optical regenerator, though no disclosure is given of how the clock could be derived from the data signal, for use in the loop interferometer.

Another regenerator using a Sagnac interferometer, which is a type of loop interferometer, is shown in Electronics Letters, 2 July 1992, volume 28, no. 14 "All Optical Regenerator Based on Non-Linear Fibre Sagnac Interferometer", Jinno et al. Again, timing and amplitude restoration is carried out on the data stream, but no disclosure is given of how the clock might be created at the regenerator.

A problem with such loop type interferometer samplers or regenerators, is that they turn out to be impractical in real systems because the bit rate is fixed by the geometry of the devices, because they are difficult to control to achieve good results in practice, and because they would be difficult to integrate.

Another use of interferometer structures has been

proposed for optical switching, eg for optical time division multiplexing systems. All optical demultiplexing and add-drop multiplexing is disclosed in "Topical meeting on Optical Amplifiers and their Applications", July 11-13, 1996, Monterey, California, 'Optical Signal Processing Using Monolithically Integrated Semiconductor Laser Amplifier Structures', Agrawal et al. A semiconductor optical amplifier is used as a phase shifter in one arm of a two arm interferometer. The data stream to be switched is fed to both arms of the interferometer. A control signal, eg a regular pulse train for demultiplexing, is fed into one arm. Constructive or destructive interference is caused when the signals in the two arms are combined. Such an arrangement is shown in figure 1. Optical amplifiers 1, 2 are provided in each arm.

It is also known to sample optical signals using a crystal, to make eye-diagram measurements, from the 22nd European Conference on Optical Communication, 1996, Oslo, "Eye-diagram Measurement of 100 Gbit/s Optical Signal Using Optical Sampling", Takara et al. A high power sampling pulse at 200 watts and with pulse lengths of less than half a picosecond, were fed into an organic non-linear crystal. The non-linear characteristic of the crystal enables the data signal to be sampled optically, though the high powers required make the system impractical for commercial use.

It is also known to use a two arm interferometer such as a Mach-Zehnder interferometer for conversion of wavelength of a data stream and simultaneous signal regeneration, from IEEE Photonics Technology Letters, volume 8, no. 9, September 1996, "10 Gbit/s Wavelength Conversion with Integrated Multi Quantum-Well-Based Three-Port Mach-Zehnder Interferometer", Idler et al. As shown in figure 2, all optical wavelength conversion with simultaneous shaping is achieved by supplying a two arm interferometer with a continuous wave input. This is modulated by the data to produce a wavelength converted data output signal. Optical amplifiers 10 and 11 in each arm of the interferometer provide the necessary phase shift according to the data input. No retiming occurs.

There remains a need for a practical optical sampling device.

### Summary of the Invention

It is an object of the invention to provide improved methods and devices.

According to the invention there is provided a method of modulating a pulse train comprising the steps of:

inputting the pulse train to a non-loop interferometer;  
inputting an optical data stream to the interferometer, to obtain an output of the pulse train modulated according to the data stream.

This enables the data stream to be regenerated, or

retimed, using a practical device which can be integrated, and which is easily adjustable and controllable.

Advantageously, the interferometer comprises a two arm interferometer, and the pulse train is input to both arms. This type of interferometer is easier to build in integrated form, easier to control, and can handle a range of bit rates.

Advantageously, each of the two arms comprises a means for altering a condition of interference of the interferometer. This enables the interferometer to be balanced more easily.

Advantageously at least one of the arms comprises an electrically controllable means for altering a condition of interference of the interferometer. This enables easy control of the interferometer either for tuning or to enable optical and electrical inputs of data or clock signals.

Advantageously, an optical data signal is retimed by operating a pulse train, and modulating it as recited above. Retiming of optical data signals in this way without having to convert the data signal into electrical form has many applications in overcoming jitter problems, for example, with less hardware, or at greater speeds than equivalent electrical retiming methods.

Advantageously, the step of generating a pulse train comprises the step of recovering a clock from the optical data signal. In many applications clock information is not transmitted separately from the data, and needs to be recovered from the data.

Advantageously, the clock is recovered optically. Corresponding advantages to those discussed above can be achieved if the clock is recovered optically.

Advantageously, time division multiplexing of optical data signals is carried out by sampling the signals at mutually different phases, each sampling process using the modulating method recited above. Optical multiplexing can be achieved more easily with reduced jitter.

Advantageously, data signals can be multiplexed by combining them to create an optical multiplexed signal, and retiming the multiplexed signal by using it to modulate a pulse train as recited above. Retiming after multiplexing can also reduce jitter problems.

Advantageously, demultiplexing at least a portion of a time division multiplexed optical signal is carried out by generating a pulse train synchronised with the portion to be multiplexed, and sampling the portion using the modulating method recited above. Corresponding advantages apply to demultiplexing.

Advantageously, demultiplexing can be carried out by retiming the optical multiplexed signal by using it to modulate a pulse train as recited above, and demultiplexing the retimed signal. Such retiming before demultiplexing can also reduce jitter.

Advantageously, an optical transmission system is operated by transmitting an optical data signal to a receiver, and retiming the optical data signal at the receiver by using it to modulate a pulse train as recited above. Retiming at a receiver is particularly advantageous to compensate for distortions in the optical data signal

caused by the optical path.

According to another aspect of the invention there is provided a method of operating an interferometer, the interferometer comprising an optically induced means for altering a condition of interference, and an optically passive means for altering the condition of the interference, the method comprising the steps of:

inputting an optical signal to alter the interference condition,

controlling the optically passive means to vary the response of the interference condition to the optical signal. This enables better control, because optically active elements tend to have tightly interdependent gain and phase. Furthermore, noise can be reduced, and the device may be easier to manufacture.

Advantageously, the interferometer comprises a two arm type interferometer.

Advantageously, the optically induced means and the optically passive means act on the same arm. Lower overall loss can be achieved by having both elements in the same arm, since gain in one element can balance attenuation in the other element.

According to another aspect of the invention there is provided an optical sampler for sampling an optical data stream, comprising:

means for providing an optical pulse stream;  
a non loop interferometer arranged to modulate the pulse train according to the data stream.

According to another aspect of the invention there is provided an interferometer comprising:

an input for an optical signal;  
an input for a control signal;  
an optically induced means for altering a condition of interference of the interferometer in response to the optical signal; and  
an optically passive means for altering the response interference condition to the optical signal, according to the control signal.

Advantageously, the optically induced means comprises an optical amplifier. Such devices have strong amplitude and phase response at moderate power levels, and are readily integrated.

Advantageously, the electrically controlled element comprises a phase shift means. This enables easy adjustment of the interference condition.

Advantageously, interferometer further comprises control means for generating the control signal at low frequencies for tuning the response to maintain a constant output.

Advantageously a regenerator is provided comprising means for recovering a clock from the optical data

signal, and a sampling means synchronised by the recovered clock, and comprising an interferometer as recited above.

According to another aspect of the invention, there is provided an optical pulse reshaping arrangement for reshaping an input data signal, the arrangement comprising:

a first and a second stage, both having non-linear responses, wherein the first stage has a limiting action on the input data signal when the signal as input to the arrangement is at a first logic state, the second stage has a limiting action when the signal as input to the arrangement is at a second logic state.

This enables noise at each logic state to be reduced, and transitions to be made steeper.

Advantageously, the stages are arranged in series to simplify the hardware by avoiding the need to combine the outputs of the stages, and to enable better control of the overall response.

Advantageously, both stages have an inverting action, which enables undesirable portions of the response to be balanced out by the other stage.

Advantageously, the responses of the two stages are not identical in shape, to introduce an extra degree of freedom, since the overall response can then be changed by changing the relative gains of the two stages.

Such advantageous features may be combined as would be appreciated by a skilled person, and may be combined with any of the aspects of the invention as appropriate.

### **Brief Description of the Drawings**

For a better understanding of the invention and how the same may be carried into effect, it will now be described by way of example with reference to the drawings, in which:

Figure 1 and figure 2 show prior art arrangements; Figure 3 shows an interferometer arrangement according to an embodiment of the invention;

Figure 4 shows waveforms for the interferometer of figure 3 operating as a sampler;

Figure 5 shows an optical clock recovery arrangement for use in synchronising the sampler of figures 3 and 4;

Figure 6 shows in schematic form a phase comparator for use in the clock recovery arrangement of figure 5;

Figure 7A shows waveforms for the interferometer of figure 3 when operating as part of the phase comparator of figure 6;

Figure 7B shows the response of the phase comparator;

Figure 8 shows another optical clock recovery arrangement;

Figure 9 shows a non-linear function for use in the

optical clock recovery arrangement of figure 8;

Figure 10 shows a phase comparator with common mode cancellation for use in the clock recovery arrangement of figure 5;

Figure 11 shows an optical regenerator;

Figure 12 shows the optical regenerator of figure 11 in more detail;

Figures 13 and 14 show multiplexers;

Figures 15 and 16 show demultiplexers;

Figures 17 to 20 show alternative interferometer arrangements for use in sampling or clock recovery;

Figure 21 shows a two stage interferometer arrangement;

Figure 22 shows the response of a single inverting stage;

Figure 23 shows the overall response for two stages; and

Figure 24 shows waveforms for the arrangement of figure 21 operating as a sampler.

### **Detailed Description**

With reference to figure 3, which shows features of the invention, an interferometer arrangement is shown including a phase shift means 20. An optical pulse train is input at one side of the interferometer. Optical data is input at either side of the interferometer, but to only one arm of the interferometer, so as to alter the condition of interference of the interferometer. Thus the output of the interferometer, constituted by a combination of the optical signals in each arm, will depend on whether the optical signals from the two arms combine with constructive interference or destructive interference. The phase shift means 20 can be arranged so that there is constructive interference when the data is high. Alternatively, the arrangement can be made in inverting form, so that there is constructive interference when the data is low. Alternatively, the peak output, where there is constructive interference can be arranged to coincide with the data beam at some point in-between high and low levels.

Figure 4 shows input and output waveforms for the interferometer of figure 3 operating as a sampler. In this case, a pulse train A is input to both arms of the interferometer. Data in optical form is input to one of the arms. The phase shift means 20, typically implemented using a semiconductor optical amplifier, causes a phase shift in one arm, which results in the output waveform C of figure 4. For high levels of the data input signal, the pulse train is output in a similar form to the pulse train input, owing to constructive interference. Where the data level is low, owing to destructive interference, there is little or no output. Accordingly, effectively the output can be seen as the pulse train input modulated by the data, or it can be seen as samples of the data, sampled by the input pulses.

In principle, various types of non-loop interferometer could be used. The Mach-Zehnder type may be

easiest to integrate and give best results in terms of stability and ease of tuning. In principle, a Michelson type interferometer could also be used.

Figure 3 shows the data being fed in the interferometer in the opposite direction to the pulse train. This means the arrangement is simpler because the data does not need to be filtered out of the output. In principle the data could be fed into the interferometer in the same direction as the pulse train, in which case filtering would be needed to remove the data signal from the output.

Three types of applications will be described for the arrangement illustrated in figures 3 and 4. The first and second relate to optical clock recovery. The third type relates to sampling a signal to regenerate it optically without conversion to electrical form.

### Clock Recovery Applications

Figure 5 shows an optical clock recovery arrangement 50 including a phase comparator 51, a clock generator 52, and a phase loop filter 53. Conventionally, such an arrangement has been produced for electrical signals, but it has been possible to achieve an optical phase comparator only suitable for operation with optical signals on which the data is coded in RZ form.

In the clock recovery arrangement of figure 5, the phase comparator receives the optical data input signal and an optical clock generated by the generator 52. Owing to the inbuilt stability of such generators, the loop filter 53 can operate effectively with a bandwidth much lower than that of the optical data signal. Accordingly, it is feasible and less expensive to implement the clock phase control and the clock generator in electrical form, and convert the electrical clock to optical form before input to the phase comparator.

The optical phase comparator 51 is shown in schematic form in figure 6. An interferometer 61 is provided for modulating the clock with the optical data. The interferometer is biased to give a peak output when the data is somewhere between high and low states, and a reduced output at the high and low states. This enables the interferometer to be responsive to data transitions, and thus determine timing of pulses optically. The interferometer may be arranged as shown in figure 3.

Figure 7A shows the typical waveforms when the interferometer is used as a phase comparator, arranged to give peak output when the data is halfway between high and low states. As a result, if the phase of the clock drifts so as to take the clock pulses out of synchronisation with the data, the output peaks shown in waveform C of figure 7 would become changed in amplitude. Referring back to figure 6, the output pulse train would be passed through integration and low pass filtering functions 62. These would enable the phase comparator output to be independent of data patterns since there will be an averaging effect.

In practice this can be implemented by a PIN diode which would output a low speed electrical signal, typi-

cally with a bandwidth of up to hundreds of KiloHertz or a few MegaHertz, which can be fed back as shown in figure 5 to the loop filter 53, which is an analog low pass filter. The output of the filter is connected to the frequency control of the oscillator. Thus a change in the amplitude of the pulses from the interferometer could be detected as a change in the level of the integrated filtered output of the PIN diode, which could cause the frequency of the oscillator to adjust to compensate. Such phase locked loop methods are well known and will not be described here in more detail.

The output of the low frequency optical to electrical converter is the convolution of the power in these pulses with its impulse response. For conceptual simplicity, this can be thought of as approximately the integral of the power in the pulses over a response time of many thousands of pulses. Thus data with uneven amounts of ones and zeroes can be handled, provided fluctuations in the proportions of ones and zeroes don't have appreciable components at frequencies below the threshold of the converter.

The pulses output by the interferometer will be the strongest when the clock input pulses coincide with the data being at the 50% cross-over point, and will fall off with the cosine function as the data approaches a 1 or 0 symbol.

In practice the input data will not have a square waveform but may approach a raised cosine shape. In such a case the overall response of the phase detector after integration by a low pass filter is shown in figure 7B.

The phase locked loop is advantageously locked to the 0.5 level of the phase detector output, and optical delay used to obtain the desired clock to data phase. Locking to the 0.5 level of the detector output gives the maximum control range (between 0 and 0.5 unit intervals of relative phase), and uses the steepest slope on the response curve, for strong feedback of phase error.

The clock pulses are preferably generated at the full bit-rate, though sub-harmonics could be used.

Careful design and adjustment of the interferometer will enable maximum output, inverting or otherwise, when the data signal is in transition between logical states. In principle such transition could be between multilevel logic states. For two level logic the interferometer should give maximum output when the data signal has a power amplitude of 50% of the eye. To achieve this, the relative phase shift between the arms and the amount of phase shift which occurs in response to the optical data input, can be adjusted. In practice, amplitude saturation effects may also need to be considered. The optical power in the data input may cause the gain of the optical shift means to be altered or reduced. This also affects the condition of interference, and will need to be accounted for when designing the interferometer. An ideal response, ignoring gain effects, and for a narrow clock pulse, much narrower than the bit period, is proportional to the following equation:

$$\frac{\cos(\pi \text{ signal}(nT+\phi))+1}{2}$$

where  $\phi$  is the phase of the clock pulse,

T is the bit period,

n is an integer,

and signal is the average power of the data, weighed over a clock pulse, centred at that time.

In this way, a phase comparator can be implemented which enables the clock to be recovered independently of the type of coding used for the data. In particular, it can operate on NRZ data, as used in most high bit rate optical transmission systems.

Figure 8 illustrates the second optical clock recovery arrangement 70, comprising a non-linear function operating on the optical data, 71, followed by an optical narrow band filter 72 to extract the clock frequency. The use of a non-linear function enables the clock to be recovered from data such as NRZ data for which there is little energy at the clock frequency. The non-linear function creates a response at the clock frequency.

Figure 9 shows how the non-linear function 71 can be implemented by an interferometer 80, arranged as in figure 3. Instead of an input optical pulse train, because there is no separately generated clock, continuous wave light is input. This is modulated by the optical data, and the interferometer is biased to give a peak output at data transitions, as described above in relation to figure 7. If an optical pulse is output for each data transition, by the non-linear function 71, the optical narrow band filter 72 shown in figure 8 can be used to remove all but the clock frequency. Preferably the optical narrow band filter is implemented by a means of a mode-locked laser, although alternative implementations are conceivable.

For systems where there are problems such as level variations, or data patterning, that create excessive jitter, then the arrangement of figure 10 can be used. The difference between outputs of two samplers 91, 92, operating as phase comparators, are subtracted to cancel common mode effects. A delay element 93 is provided to delay the clock input of one of the phase comparators. The delay can be arranged to be such that there is a minimal response from one of the comparators when the other is giving a peak output. Thus the outputs of the samplers 91, 92, are integrated and filtered by optical to electrical converters 94 and 95. A subtractor 96 and low pass filter 97 can be used to derive an oscillator tuning signal from which common mode effects have been cancelled out.

#### Optical Regeneration and Other Applications of Optical Sampling

The optical clock recovery circuits discussed above

can be used in receivers or regenerators. They can be used in conjunction with electrical signal reshaping and retiming, or used with optical retiming and reshaping functions, to create an all optical regenerator, as shown in figure 11. Sampler 100 is fed by the output of the optical clock recovery function 101. A similar arrangement may occur at a receiver, where the optical sampler 100 is used for retiming and reshaping the optical data prior to conversion to electrical form, and subsequent processing such as demultiplexing.

Figure 12 shows the optical regenerator of figure 11 in more detail. The sampler 100 comprises an interferometer, biased to give maximum output when the data input is in a given logical state. The optical recovery circuit 101 also comprises an interferometer, this time biased to produce a peak output on data transitions, to enable it to function as a phase comparator. A semiconductor optical amplifier 102 acts as the optically active element for changing the interference condition of the interferometer, according to the data signal fed into the same arm of the interferometer. Phase shift means 103 is provided for biasing the interferometer to achieve the desired function. A low pass filter 104 and optical clock 105 complete the phase locked loop, to lock the optical clock to the transitions in the data.

In the sampler 100, a semiconductor optical amplifier (SOA) is again provided to alter the interference condition according to the data signal, and phase shift means 107 is provided to bias the interferometer to achieve the sampling function.

In this way, an all optical regenerator can be achieved capable of handling NRZ data and capable of being integrated for cost effective regeneration, particularly suitable for higher bit rate transmission systems where electrical regeneration becomes more difficult and expensive.

Figure 13 and 14 show applications of the optical sampler as illustrated in figure 12 or in figure 3, in multiplexer arrangements.

Figure 13 shows a multiplexer arrangement in which multiplexing is carried out by optical or electrical multiplex means 110, and then an optical sampler 111 is provided to retune and reshape the combined signal, for onward transmission. Synchronisation is provided by clocks 112. Two clocks could be provided to the multiplexer 110 to switch the two incoming data streams appropriately to enable time division multiplexing. This could be on the basis of a bit interleave scheme, though other well known schemes are conceivable. Although only two data inputs are shown, obviously there could be more.

An alternative multiplexer arrangement using the optical sampler described above, is shown in figure 14. An optical sampler 111 is provided for each of the optical data inputs to be multiplexed. Separate clocks are provided for each sampler so as to sample each optical data input at a different time interval. The mutually out of phase output samples can then be combined optically

to produce a single multiplexed optical data output stream.

Figures 15 and 16 show corresponding demultiplexing arrangements using the optical sampler described above. In figure 15 the sampler 111 is used to retime and reshape the incoming optical data stream. This enables the optical or electrical demultiplexer 120 to be of lower performance specification, since it is fed with a clean optical signal with little jitter.

Figure 16 shows an alternative arrangement, in which multiple optical samplers 111 are fed with the same input data stream. Separate clocks are provided for each sampler so that samples are taken at different times by different samplers. This enables the time division multiplexed data to be separated out.

In principle, the demultiplexer arrangements of figures 15 and 16 could be used to decode multilevel logic signals. Different samplers could be biased individually so as to give a maximum output for different amplitude levels.

### Interferometer Operation and Arrangements

As an alternative to the interferometer arrangement shown in figure 3, figure 17 shows an arrangement in which the optically active element, the optical amplifier is provided in both arms of the interferometer. This makes it easier to balance the interferometer. In principle, the interference condition of the interferometer, and therefore the response at the output, is dependent on the amplitude of the modulation of the optical waveform, and on the phase of the optical waveform in each arm, ignoring polarisation effects. The optical amplifiers 130 and 131 in figure 17 can alter the interference condition. When data is input to the arm containing optical amplifier 131, the interference condition will be changed because the optical amplifier has an amplitude to optical phase conversion effect. Ideally, the pulses input to both arms, are sufficiently short and have sufficiently low energy that the SOA does not react much to the pulses. However, the SOA should have a sufficiently rapid response time to react to the data waveform. The pulses input to both arms of the interferometer can therefore be very narrow, as there is no limit imposed by the speed of the response of the SOAs. Furthermore, it is relatively easy to generate very narrow light pulses, on the order of several picoseconds or less.

Construction of an integrated Mach-Zehnder interferometer for use with high bit rates and with good performance characteristics is described in IEEE Photonics Technology, Volume 8, September 1996 "Ten Gbs Wavelength Conversion With Integrated Multiquantum-Well-Based Three-Port Mach-Zehnder Interferometer" by Idler et al. The structure is grown by low pressure metal organic vapour phase epitaxy. The device described can be used either for outputting inverted or non-inverted data, with respect to the signal input data. Although it is described for the purpose of wavelength con-

version, based on inputting a continuous wave into both arms of the interferometer, such a device could be used for the application as described above.

Figure 18 shows an alternative arrangement in which a continuous wave bias is fed in in addition to the input pulses. This enables the operating point of the amplifiers to be set. A filter 140 would be required to remove the continuous wave from the output. In this figure and in figure 17, an output path at the top right is shown, which is unused, and provided only for balancing the arrangement.

Figure 19 shows another interferometer arrangement in which one of the optical amplifiers is replaced with an electrically controlled phase shifter. An example of such a phase shifter is described in Photonics Technology Letters, June 1990, pages 404 to 406, and Photonics Technology Letters, August 1996, pages 1018 to 1020 (Rolland et al). The gain/loss of the arm containing the phase shifter can be adjusted to match that in the arm containing the SOA. The phase shifter can be used to set the desired condition of interference, to enable peak output for the data input logic state being high, or low, or somewhere in between, as desired.

One advantage of using such an optically passive device is that less ASE (amplified spontaneous emission) noise is generated. Furthermore, by using a phase shift device with little or no gain variation, the interference condition can be controlled more easily, since there is independent control of gain and phase differences between the two arms.

The electrically controlled phase shifter need only operate at low frequencies, eg below 1 Megahertz, when only used for tuning. If a high frequency phase shifter were to be provided, then combined optical and electrical data inputs could be handled.

Figure 20 shows another interferometer arrangement. If the phase shifter 160 is placed in the same arm as the SOA 161, the other arm becomes a simple transmission line. This has the advantage of better balance in the losses between the two arms. The phase shift will tend to attenuate the signal. The SOA can compensate for this by amplifying the signal. Electrically tuned attenuators could also be added to either arm, to balance the power levels. Other elements which have an optical phase shift in response to an optical power level could be used in place of the SOA. Other interferometer configuration such as a Michelson arrangement could be used. The entire device could be integrated for a low cost high volume production, using methods such as those discussed by Rolland et al.

All the arrangements discussed could be used either in the sampler or the phase detector or the non-linear response applications of the interferometer. A two stage interferometer arrangement will now be discussed with reference to figure 21, which is particularly applicable to the sampler.

### The Two Stage Interferometer Arrangement

Figure 21 shows an arrangement which would be suitable for replacing the single interferometer of the sampler in figure 12. The first stage comprises an interferometer having SOAs 170 and 171. Continuous wave light is fed into both arms, and data is fed into one arm. The gain in the first stage can be arranged to be sufficient to drive the first stage output to its limit for one level of input data (high or low depending on whether the stage is to be inverting or not). This effectively makes gradual data transitions steeper, and flattens one of the logic states.

The second stage can be arranged to drive its output to its limit for the other logic level. Thus the data can be reshaped optically. If no retiming is required, but only reshaping, the second stage could be fed with continuous wave light. Alternatively, the retiming could be implemented by feeding the first stage with a pulse train.

Figure 22 shows the output power for the first stage versus input power, where the first stage is an inverting stage. For a logical zero data input, the power output is high, driving the output to its limit, and thus flattening the logic level 1 of the output. The output of the first stage should follow a response curve which is less steep than a  $1/x$  curve at low input powers, and is flatter than the  $1/x$  curve at higher input powers, but steeper at intermediate powers. Such a shape, when used in two stages results in the overall response shown in figure 23. For good sampling of data and to produce steep transitions, the transition range should be as short as possible. Furthermore, the transition range should be located so as to be centred around the threshold between high and low logic states for the input signal. If inverting devices are used, the transition can be centred more easily since the inversion causes the second stage response to balance the steepest portion of the first stage response, rather than accentuate it.

In principle, a device with more than two stages could be constructed. Furthermore, the stages could be in parallel rather than in series. If in parallel, some sort of time division multiplexing for the two logic states would be required. Furthermore, the stages could be non-inverting, though for interferometers at least, the inverting response is preferable. Optical devices other than interferometers could be used if they have a non-linear response similar to that shown in figure 22.

For good optical regeneration of data, a short transition range will determine how steep the transitions of the change in interference condition of the second interferometer are. In turn, this can effect the sampling process which takes place in the second stage. If the second stage is fed by continuous wave light, the steepness of transition in interference condition will determine the shape of the output data transitions.

Figure 24 shows at waveform A the data input. The output of the first inverting interferometer is shown in waveform B, which has steeper transitions than wave-

form A. The pulse train of waveform C is the other input to the second interferometer. Waveform D shows how the interference condition of the second interferometer is dependent on the output of the first interferometer.

The limiting action of the first interferometer would remove noise from the signal for the period when the data input is in a high state. However, noise at the low state of the data input, would remain on the output of the first inverting interferometer. However, the interference condition of the second interferometer, shown in waveform D, would exhibit little noise on either the high level state or the low level state. Furthermore, the transitions in waveform D would be even steeper than those in waveform B, owing to the response of the type shown in figure 22. This leaves a relatively wide "eye", for the sampling pulse of the pulse train in waveform C. Accordingly, the output waveform E in figure 24 will be relatively free of noise, and relatively immune to jitter in the data input.

For devices or arrangements where there is a limited amount of gain, and therefore only moderate limiting, the regeneration performance may not be as good in terms of jitter immunity and noise reduction, as can be achieved with electrical regeneration. For example, if the gain is limited to a factor of 3, a signal at 10% above the threshold between high and low, might be increased to 30% above the threshold. If the threshold is set at 50% of the maximum signal, then the output would be up to 80% of the maximum, and therefore the limiting action would be only partial. Nevertheless, it would clearly be beneficial, even without complete limiting up to 100% of the signal range.

If the response curves for the two individual stages are not identical, then the overall response shape can be altered by altering the relative gains of the two stages. This adds an extra degree of freedom. In designing the device, the amplification characteristics of the optical amplifiers in the interferometers can be varied. The relative powers of the three inputs, the data input, the continuous wave input, and the pulse train input, can be varied. Furthermore, the coupling between the two stages can be varied. In this way, the two stage device offers more flexibility for tailoring the response to the needs of the particular application.

There are a number of applications where such partial optical regeneration would be useful. Firstly, inside an optical amplifier, eg a bi-directional optical amplifier, having multiple stages, improved performance could be achieved if the output of a first stage of amplification was subject to such partial optical regeneration, before passing through a filter and into a second stage of amplification. Noise and jitter could be reduced.

Secondly, inside an optical switch, it could be useful to have partial optical regeneration to avoid accumulation of degradations.

Finally, partial optical regeneration would be useful if applied between WDM subnetworks, for purposes of at least partial isolation, so that each subnetwork could

be operated and specified independently of the degradations occurring in neighbouring networks.

Other variations will be apparent to a person skilled in the art, falling within the scope of the claims.

#### Claims

1. A method of modulating a pulse train comprising the steps of:
  - inputting the pulse train to a non-loop interferometer;
  - inputting an optical data stream to the interferometer, to obtain an output of the pulse train modulated according to the data stream.
2. The method of claim 1 wherein the interferometer comprises a two arm interferometer, and the pulse train is input to both arms.
3. The method of claim 2 wherein each of the two arms comprises a means for altering a condition of interference of the interferometer.
4. The method of claim 2 or 3 wherein at least one of the arms comprises an electrically controllable means for altering a condition of interference of the interferometer.
5. A method of retiming an optical data signal comprising the steps of:
  - generating a pulse train;
  - modulating the pulse train using the method of any preceding claim.
6. The method of claim 5 wherein the step of generating a pulse train comprises the step of recovering a clock from the optical data signal.
7. The method of claim 6 wherein the clock is recovered optically.
8. A method of time division multiplexing optical data signals, comprising the steps of:
  - sampling the optical data signals at mutually different phases, each sampling process using the method of any of claims 1 to 4; and
  - combining the sampled data signals.
9. A method of multiplexing signals comprising the steps of:
  - combining the signals to create an optical multiplexed data signal; and
  - retiming the multiplexed data signal by using it
- to modulate a pulse train according to the method of any of claims 1 to 4.
10. A method of demultiplexing at least a portion of a time division multiplexed optical signal comprising the steps of:
  - generating a pulse train synchronised with the portion to be demultiplexed; and
  - sampling the portion using the method of any of claims 1 to 4 to separate it from the multiplexed signal.
11. A method of demultiplexing an optical multiplexed data signal comprising the steps of:
  - retiming the signal by using it to modulate a pulse train according to the method of any of claims 1 to 4; and
  - demultiplexing the retimed signal.
12. A method of operating an optical transmission system comprising a transmitter and a receiver, the method comprising the steps of:
  - transmitting an optical data signal to the receiver, and
  - retiming the optical data signal at the receiver by using it to modulate a pulse train according to the method of any of claims 1 to 4.
13. A method of operating an interferometer, the interferometer comprising an optically induced means for altering a condition of interference, and an optically passive means for altering the condition of the interference, the method comprising the steps of:
  - inputting an optical signal to alter the interference condition,
  - controlling the optically passive means to vary the response of the interference condition to the optical signal.
14. The method of claim 13 wherein the interferometer comprises a two arm type interferometer.
15. The method of claim 14 wherein the optically induced means and the optically passive means act on the same arm of the interferometer.
16. An optical sampler for sampling an optical data stream, comprising:
  - means for providing an optical pulse train;
  - a non loop interferometer arranged to modulate the pulse train according to the data stream.
17. The sampler of claim 16 wherein the interferometer comprises a two arm type interferometer.

18. The sampler of claim 16 or 17 wherein the interferometer comprises an optically induced means for altering a condition of interference of the interferometer.

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19. The sampler of claim 18 wherein the optically induced means comprises a semiconductor optical amplifier.

20. The sampler of any of claims 16 to 19 further comprising a means for electrically controlling the response of a condition of interference of the interferometer to the data signal.

10

21. A regenerator for regenerating an optical data signal, comprising:

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the sampler of any of claims 16 to 20; and  
a clock recovery means for recovering a clock from the optical data signal.

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22. An optical terminal for an optical transmission system, comprising:

the sampler of any of claims 16 to 20; and  
means for converting the data stream between electrical and optical form.

25

23. An interferometer comprising:

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an input for an optical signal;  
an input for a control signal;  
an optically induced means for altering a condition of interference of the interferometer in response to the optical signal; and  
an optically passive means for altering the response interference condition to the optical signal, according to the control signal.

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24. The interferometer of claim 23 wherein the optically induced means comprises an optical amplifier.

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25. The interferometer of claim 23 or 24, wherein the optically passive means comprises an electrically controlled element.

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26. The interferometer of claim 25 wherein the electrically controlled element comprises a phase shift means.

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27. The interferometer of any of claims 23 to 26 further comprising control means for generating the control signal at low frequencies for tuning the response to maintain a constant output.

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28. A regenerator for regenerating an optical data signal, comprising:

means for recovering a clock from the optical data signal; and  
a sampling means synchronised by the recovered clock, wherein the sampling means comprises the interferometer of any of claims 23 to 27.

29. An optical pulse reshaping arrangement for reshaping an input data signal, the arrangement comprising:

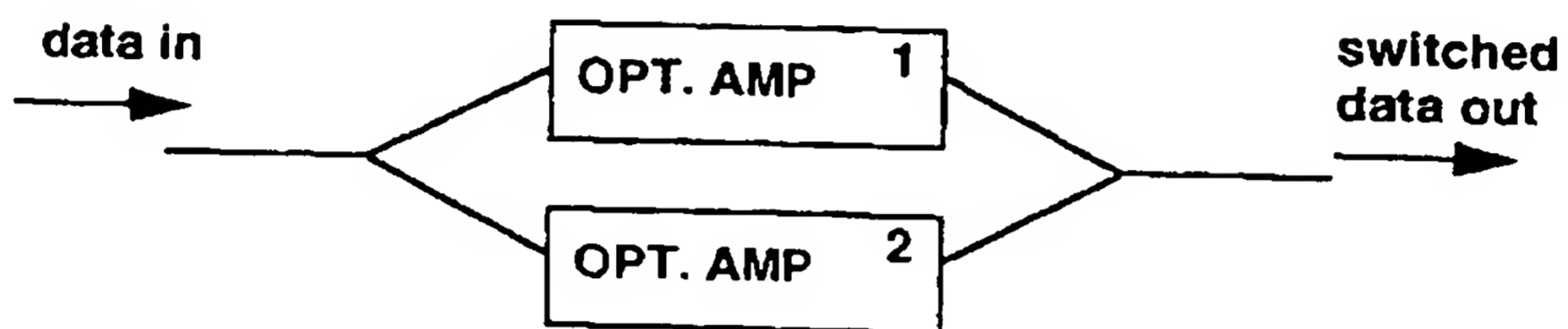
a first and a second stage, both having non-linear responses, wherein the first stage has a limiting action on the input data signal when the signal as input to the arrangement is at a first logic state, the second stage has a limiting action when the signal as input to the arrangement is at a second logic state.

30. The arrangement of claim 29 wherein the two stages are arranged in series.

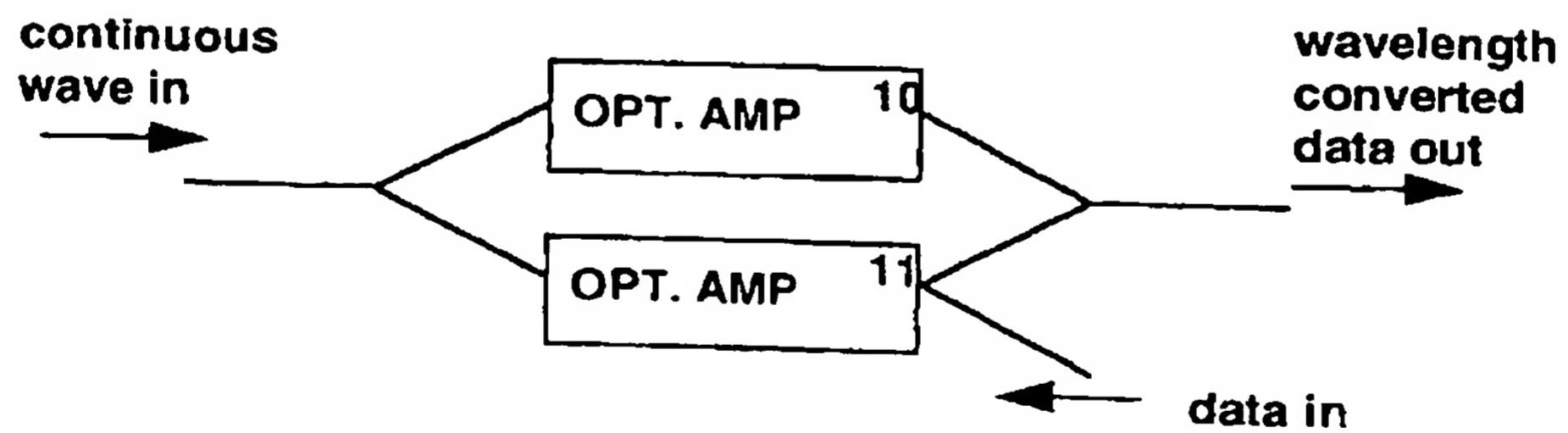
31. The arrangement of claim 29 or 30 wherein both stages have an inverting action.

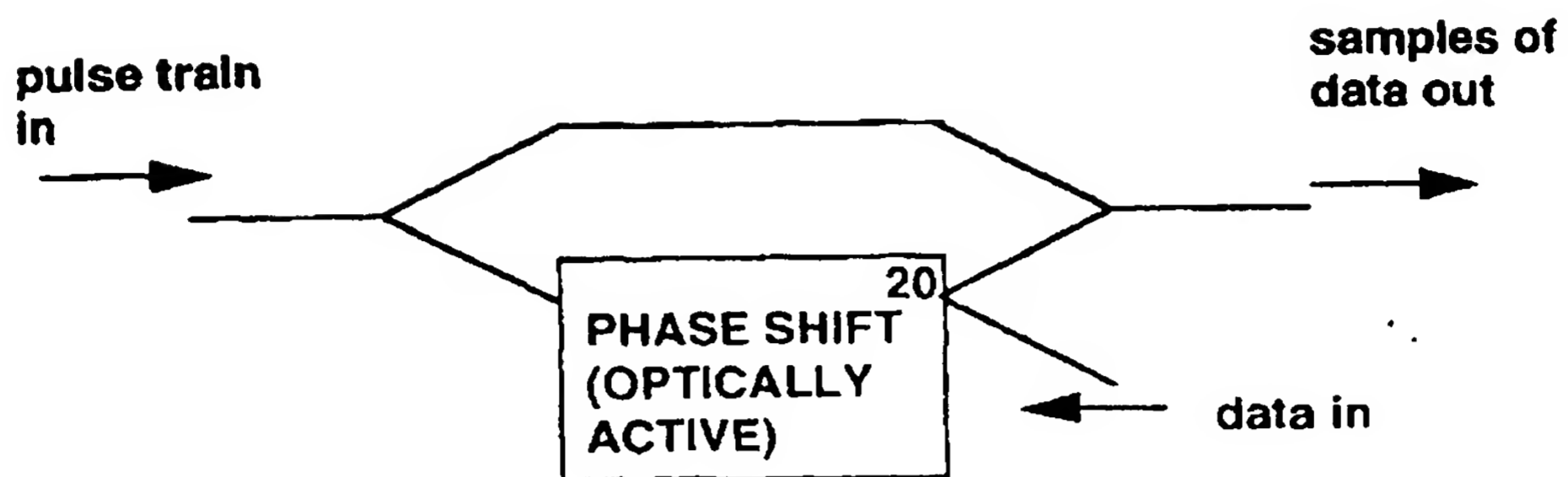
32. The arrangement of any of claims 29 to 31 wherein the non-linear responses of the two stages have different shapes.

**Fig 1 PRIOR ART**  
INTERFEROMETER ARRANGEMENT FOR SWITCHING

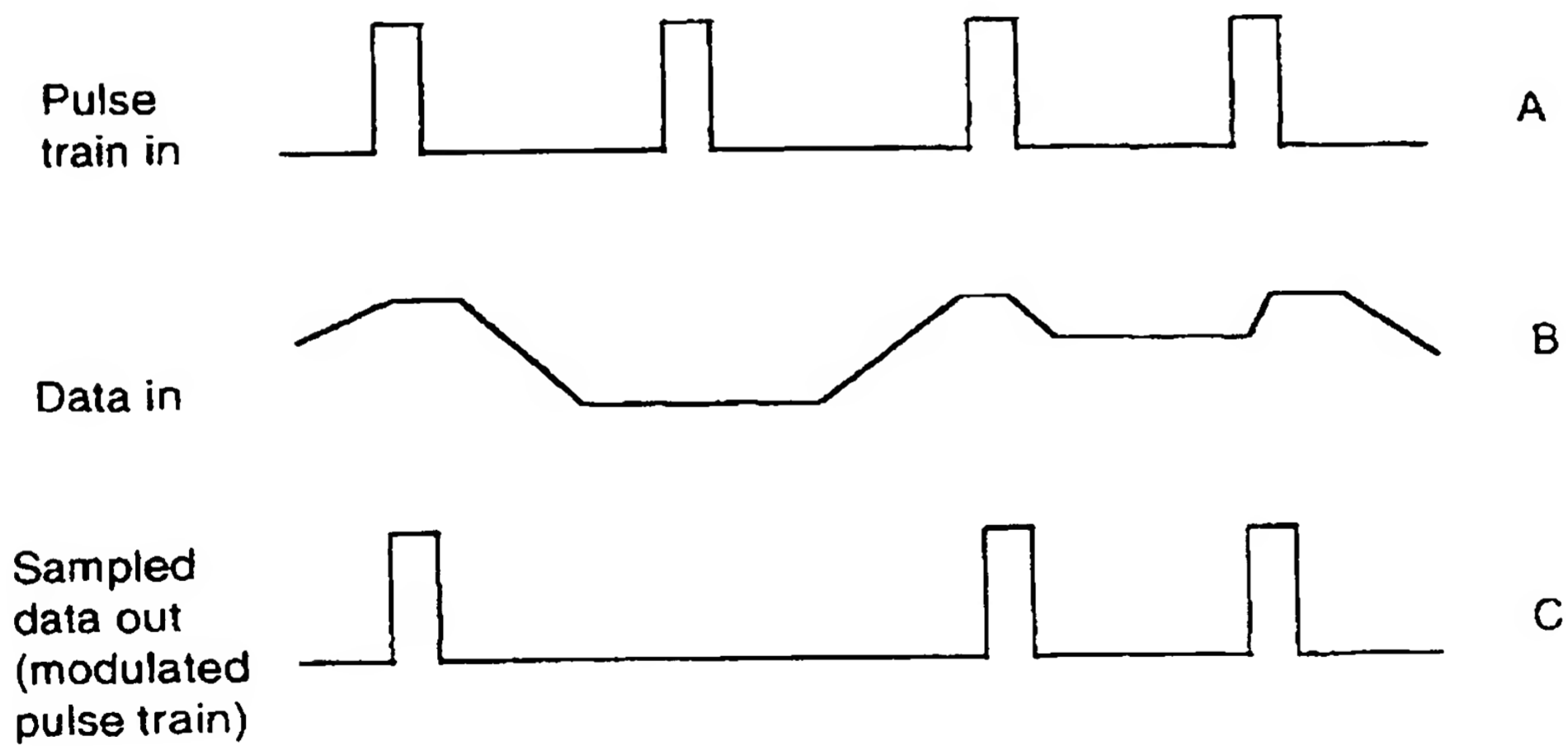


**Fig 2 PRIOR ART**  
INTERFEROMETER ARRANGEMENT FOR  
WAVELENGTH CONVERSION





**Fig 3**  
INTERFEROMETER ARRANGEMENT



**Fig 4**  
INTERFEROMETER OPERATING AS SAMPLER

Fig 5

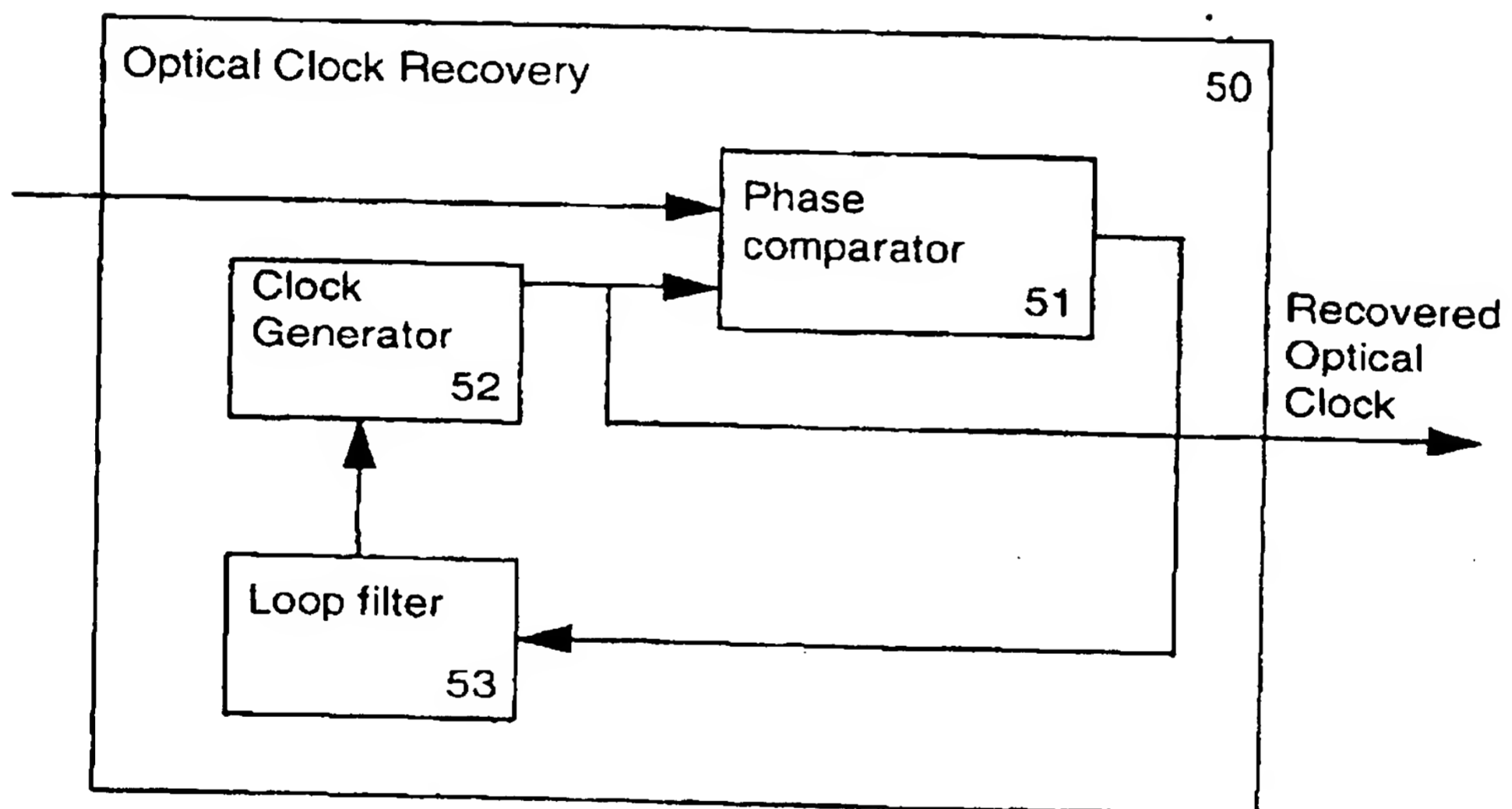
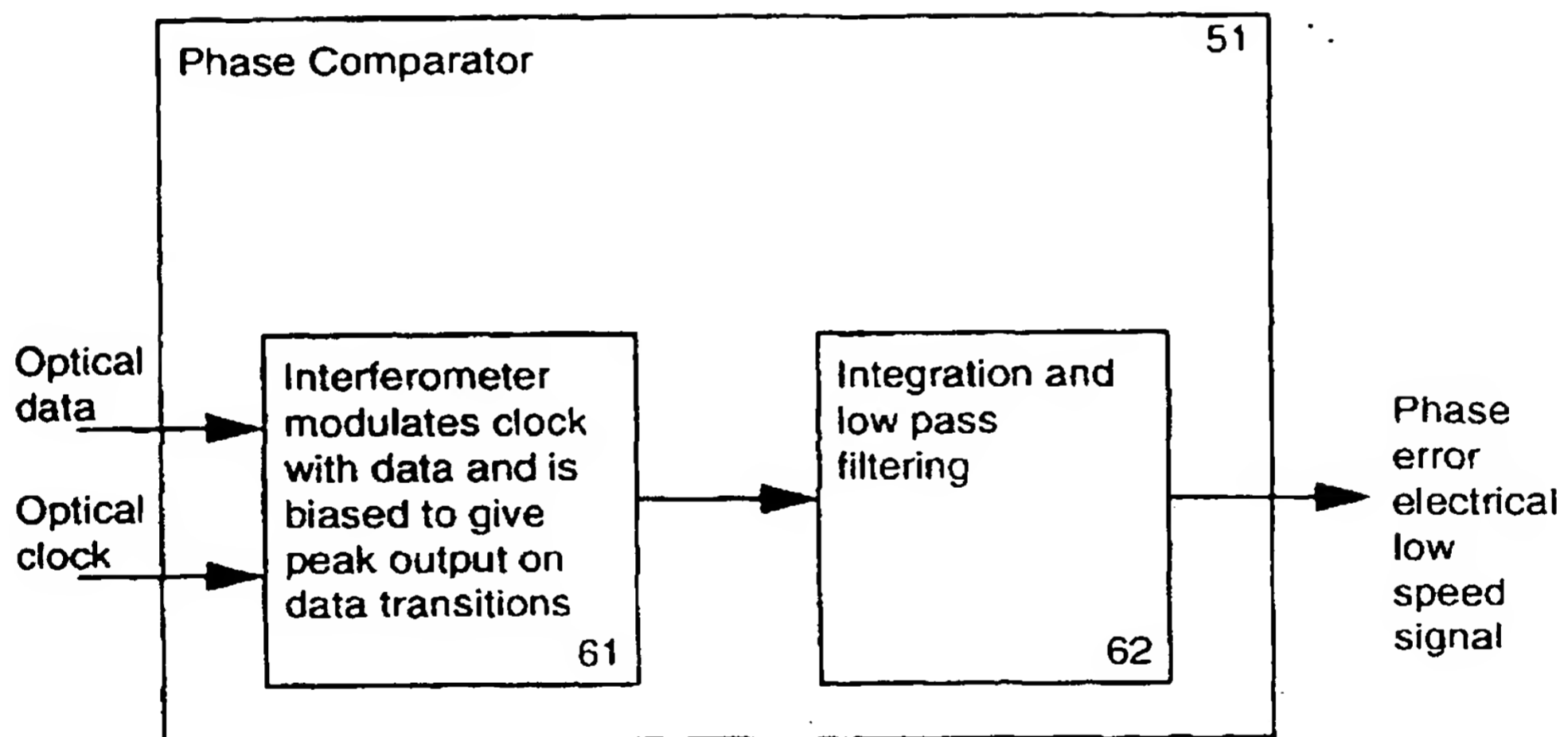
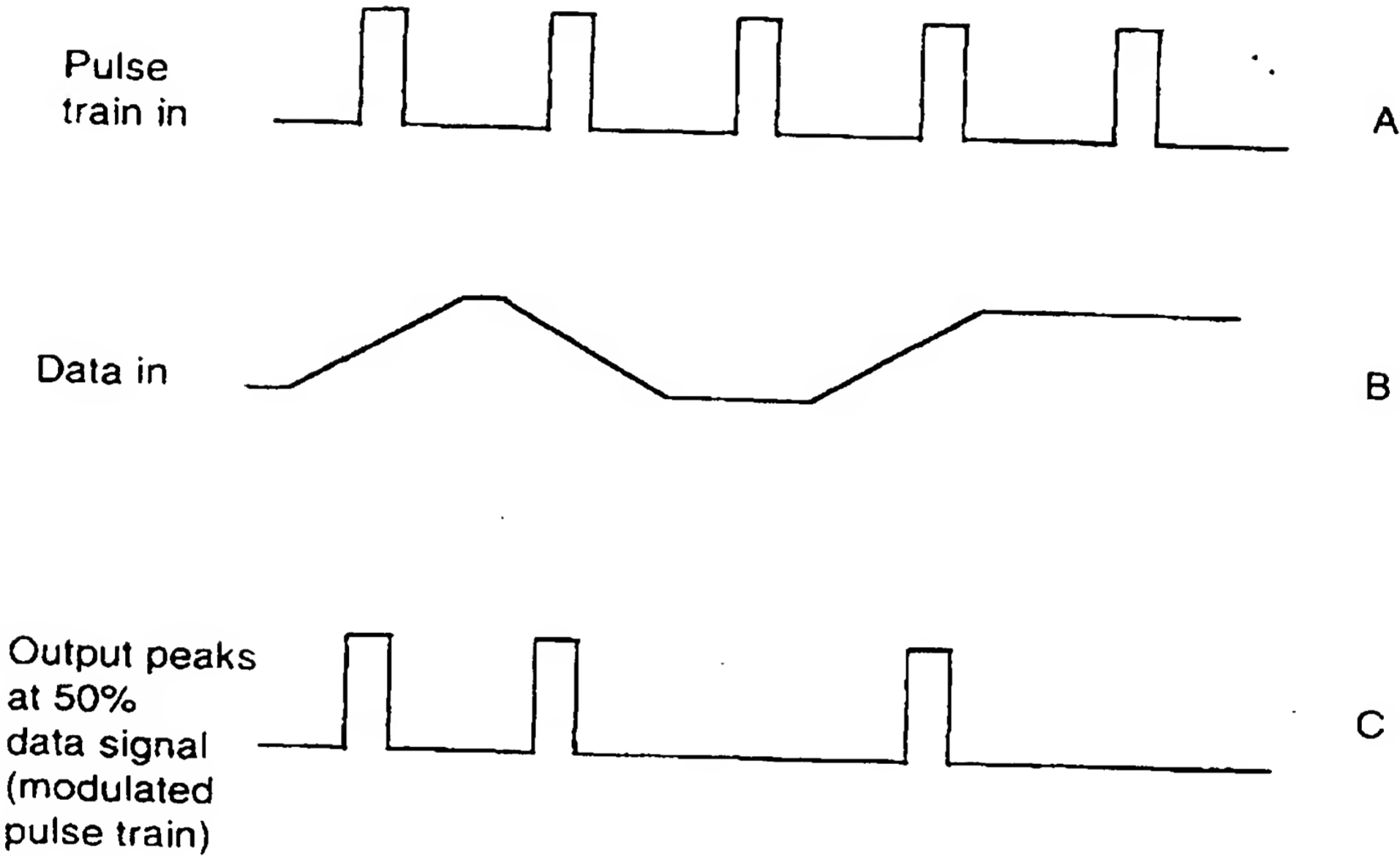


Fig 6





**Fig 7A**  
**INTERFEROMETER OPERATIVE AS PHASE**  
**COMPARATOR**

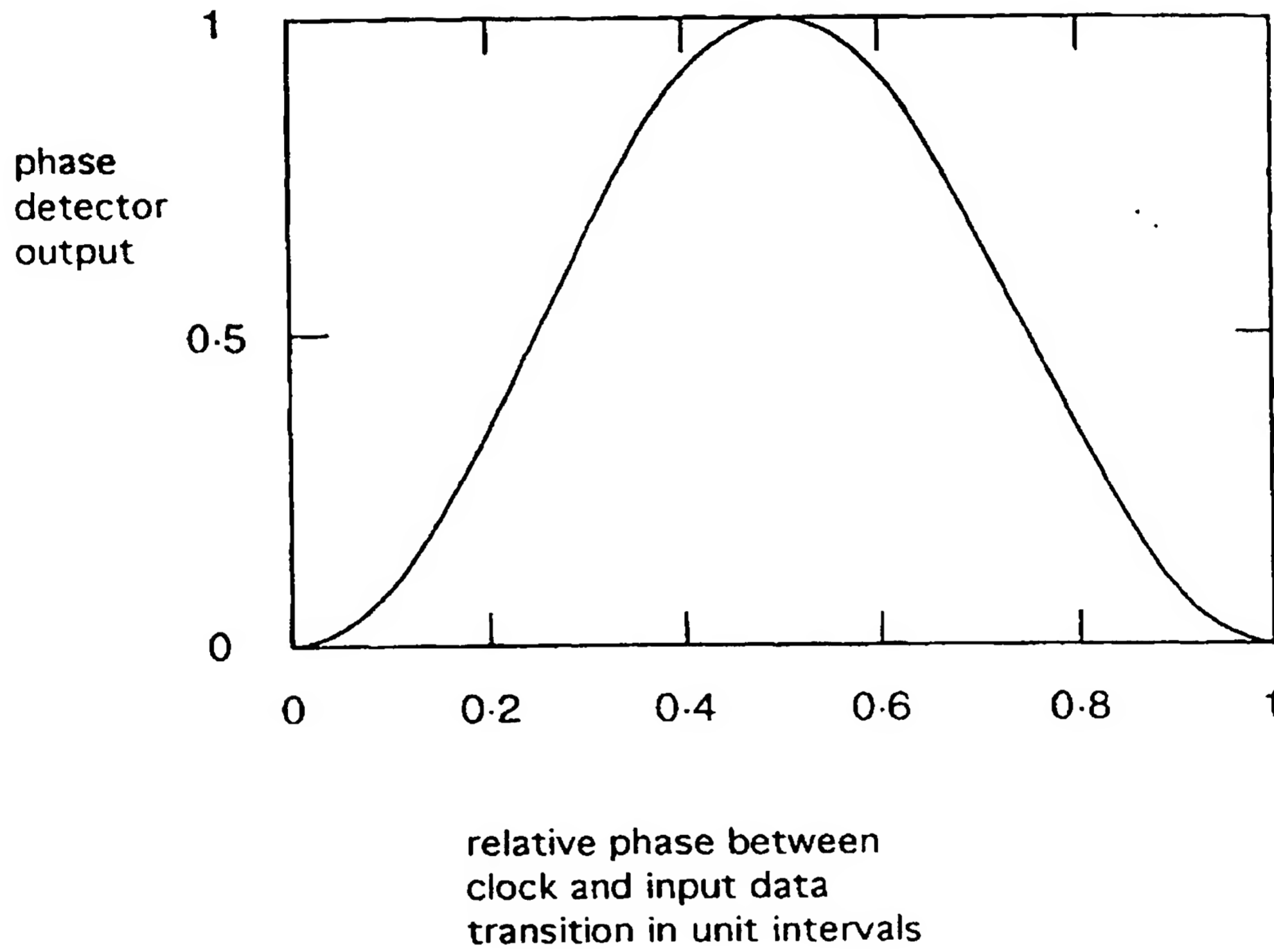
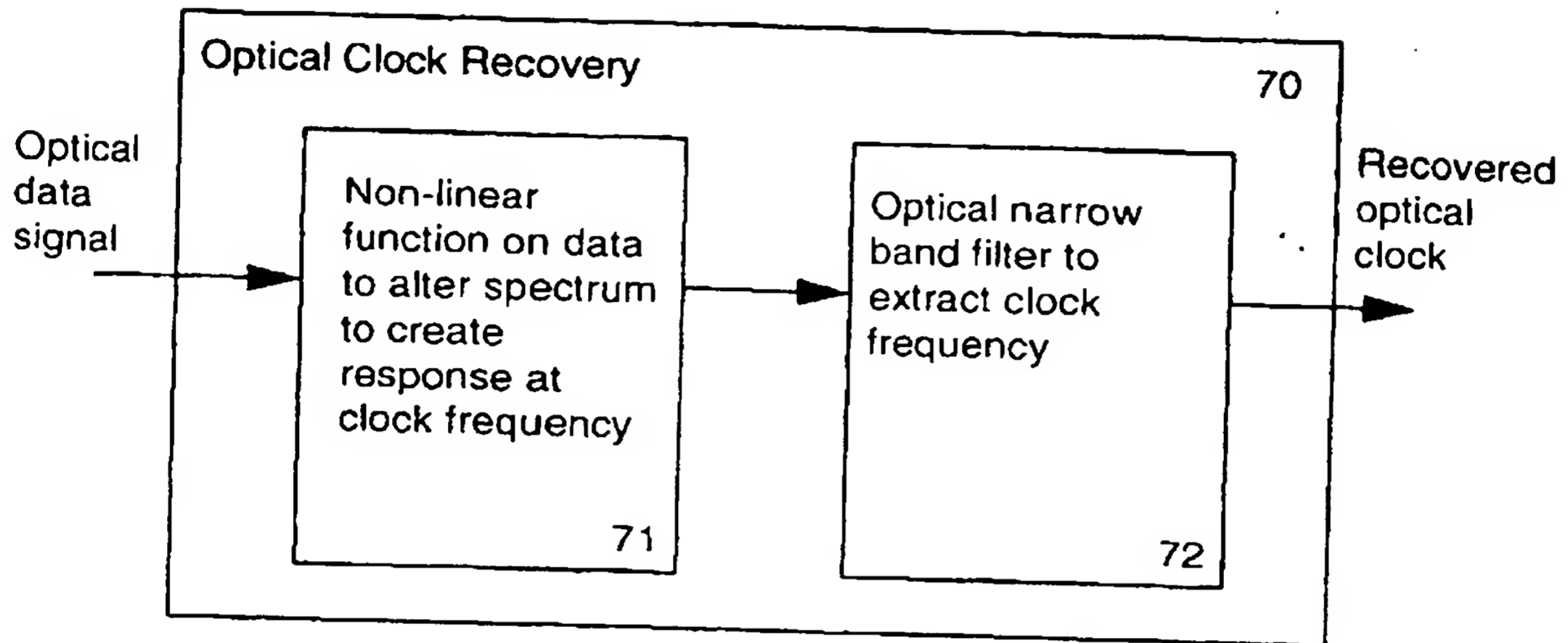


Fig 7B

**Fig 8**



**Fig 9**

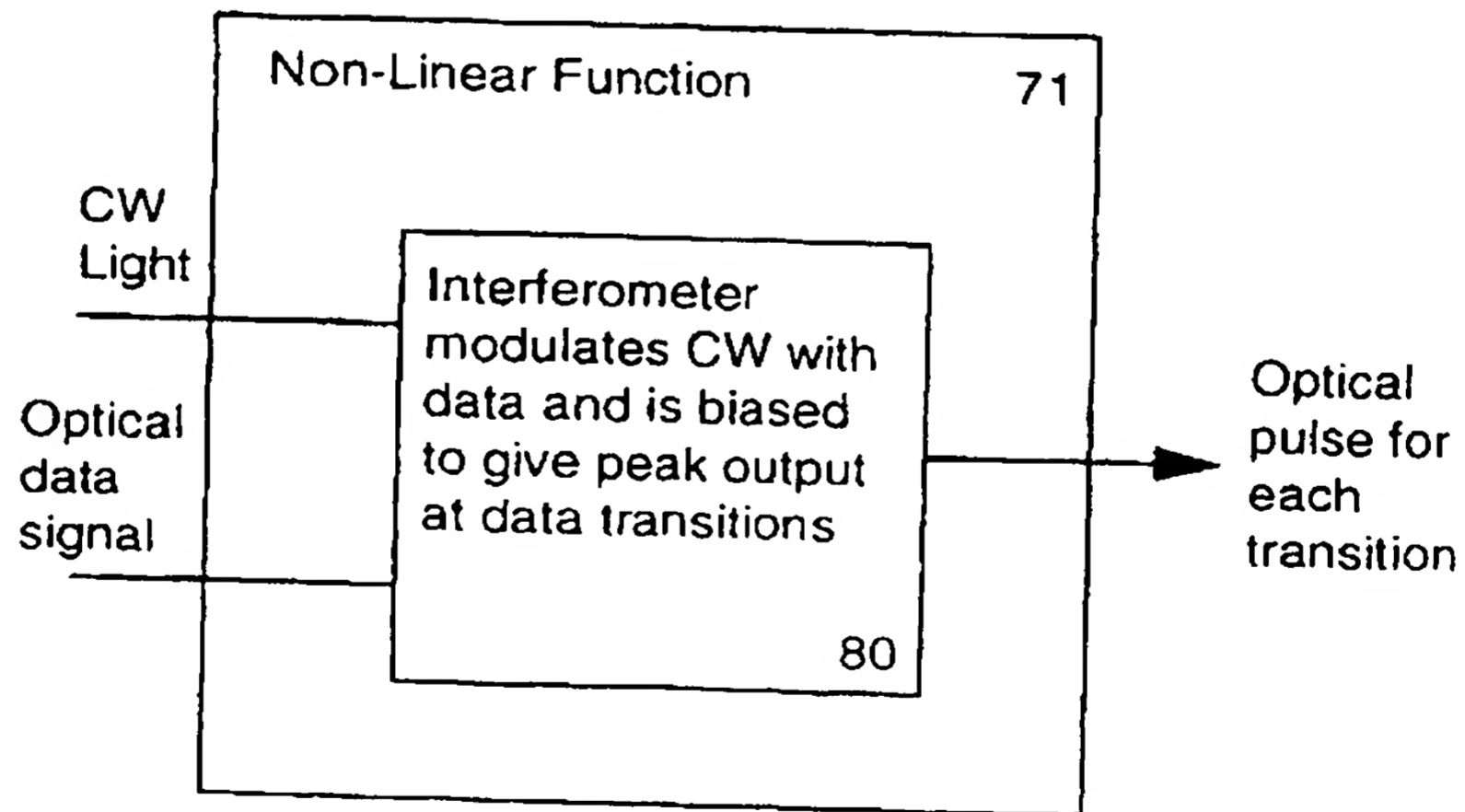
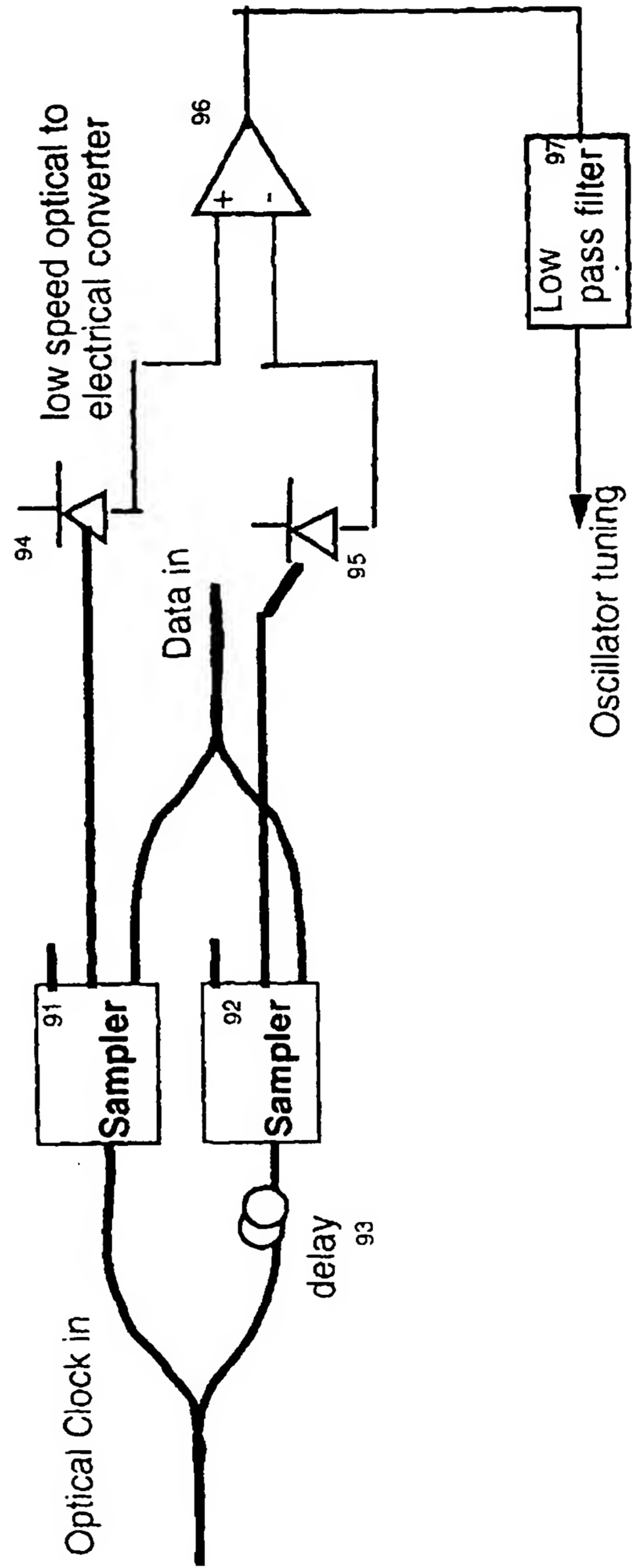


Fig 10 Phase Comparator with Common Mode Cancellation



**Fig 11**  
**OPTICAL REGENERATOR**

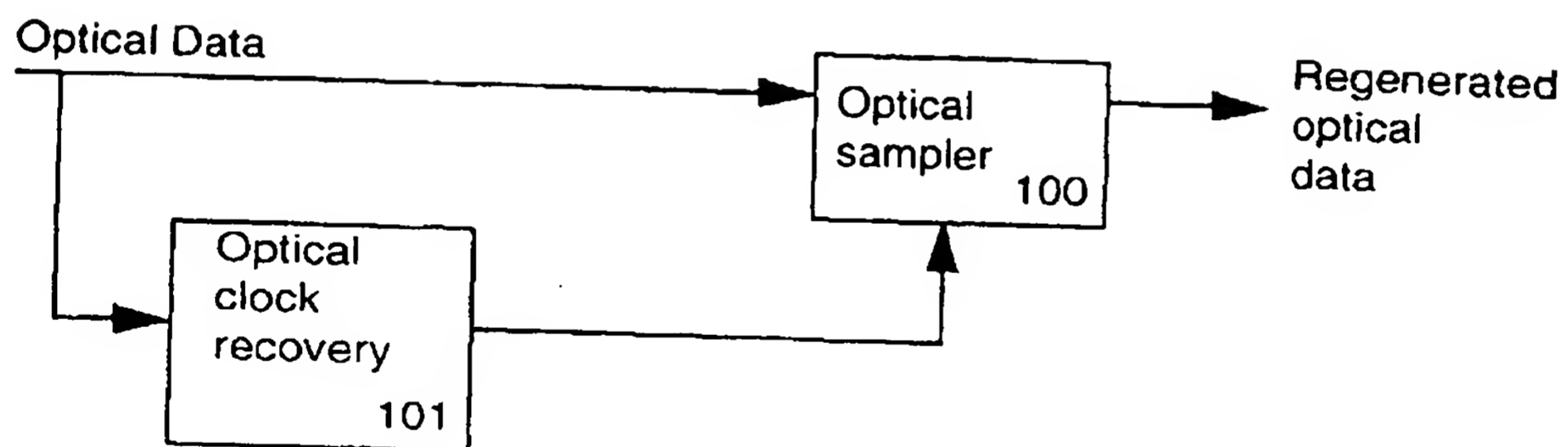
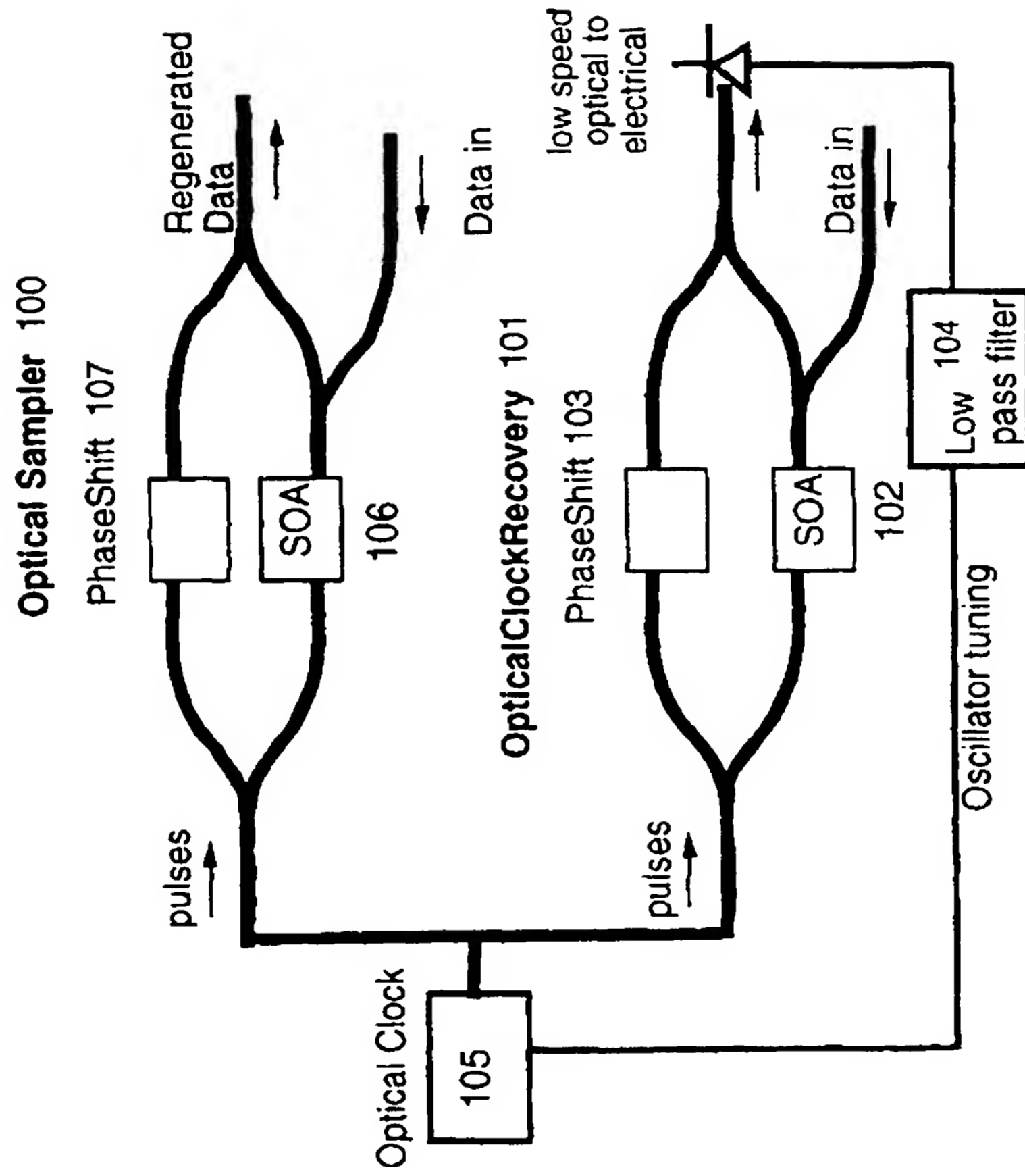
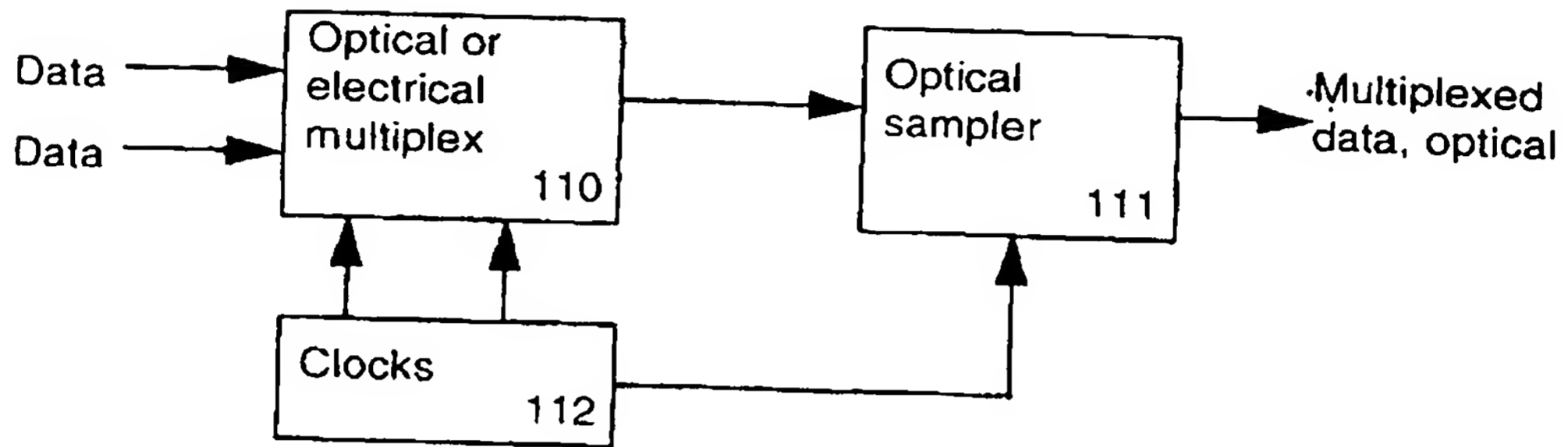


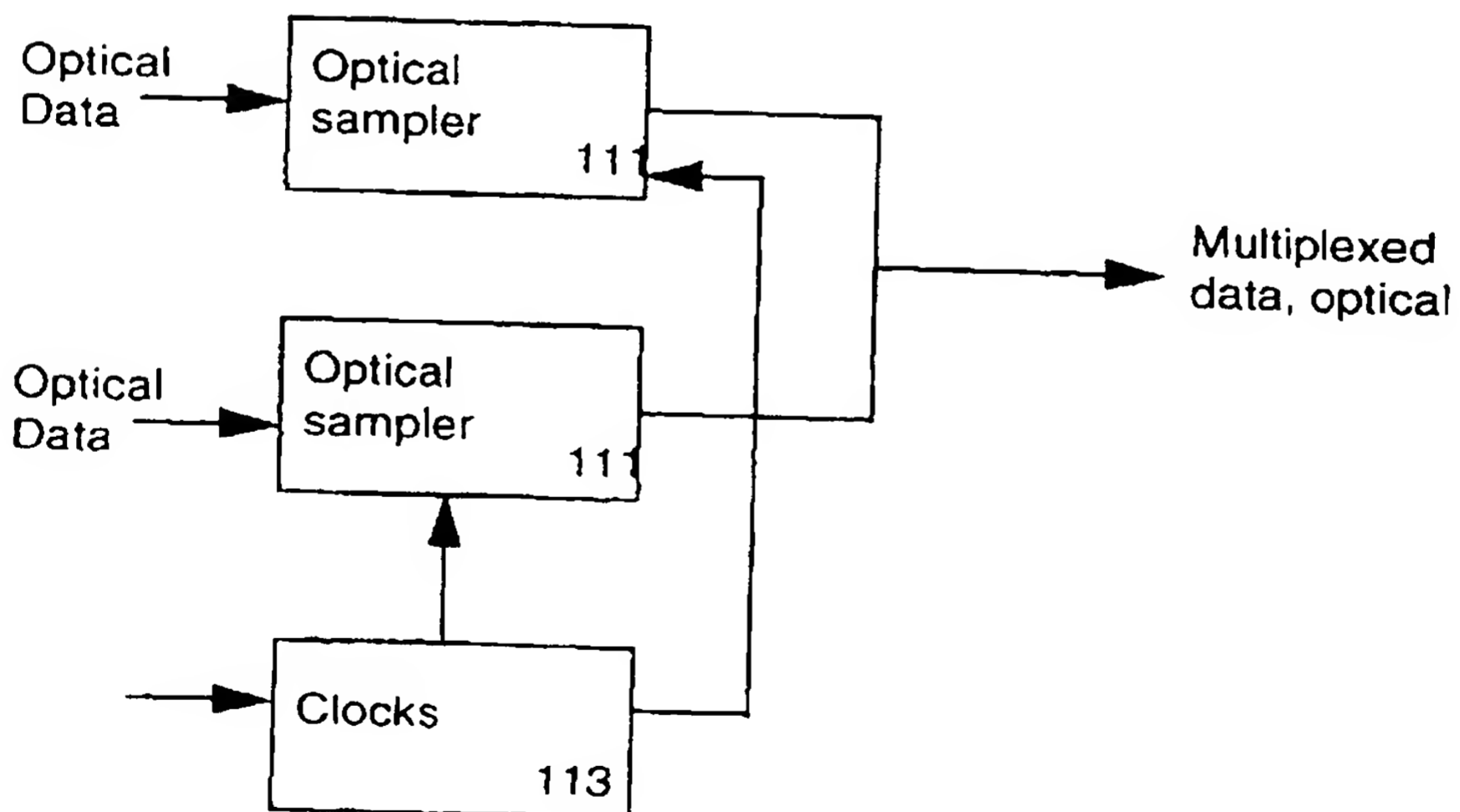
Fig 12 Optical Regenerator



**Fig 13**  
**MULTIPLEXER**

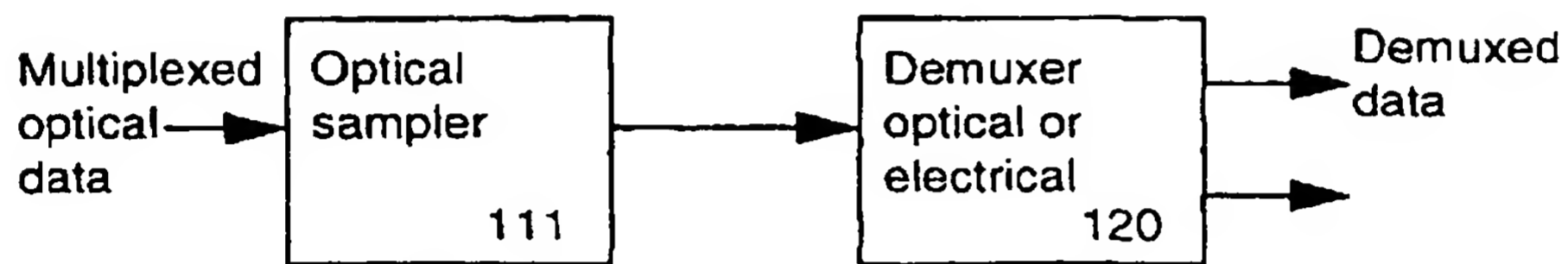


**Fig 14**  
**MULTIPLEXER**



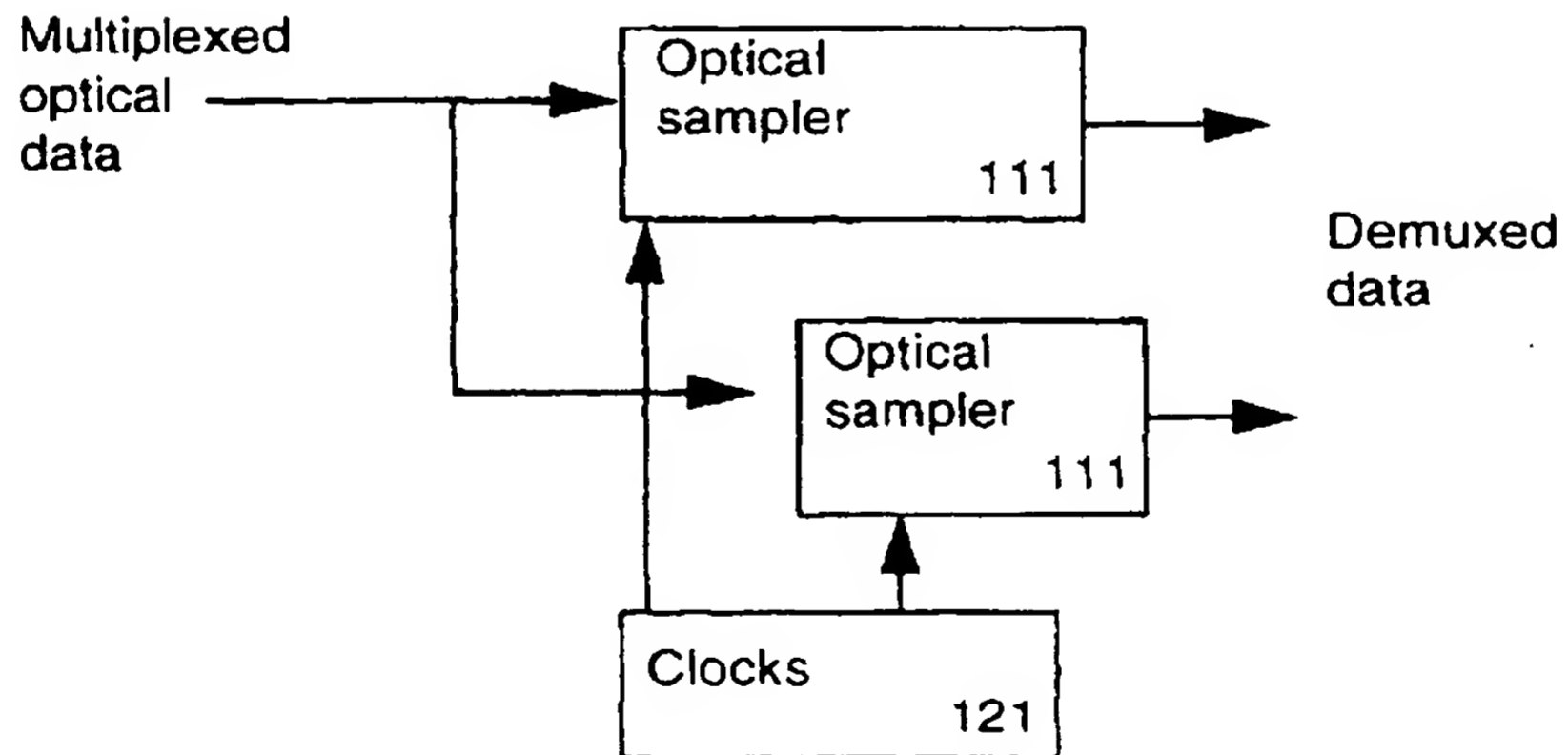
**Fig 15**

**DEMULTIPLEXER**



**Fig 16**

**DEMULTIPLEXER**



**Fig 17**  
Interferometer  
Arrangement

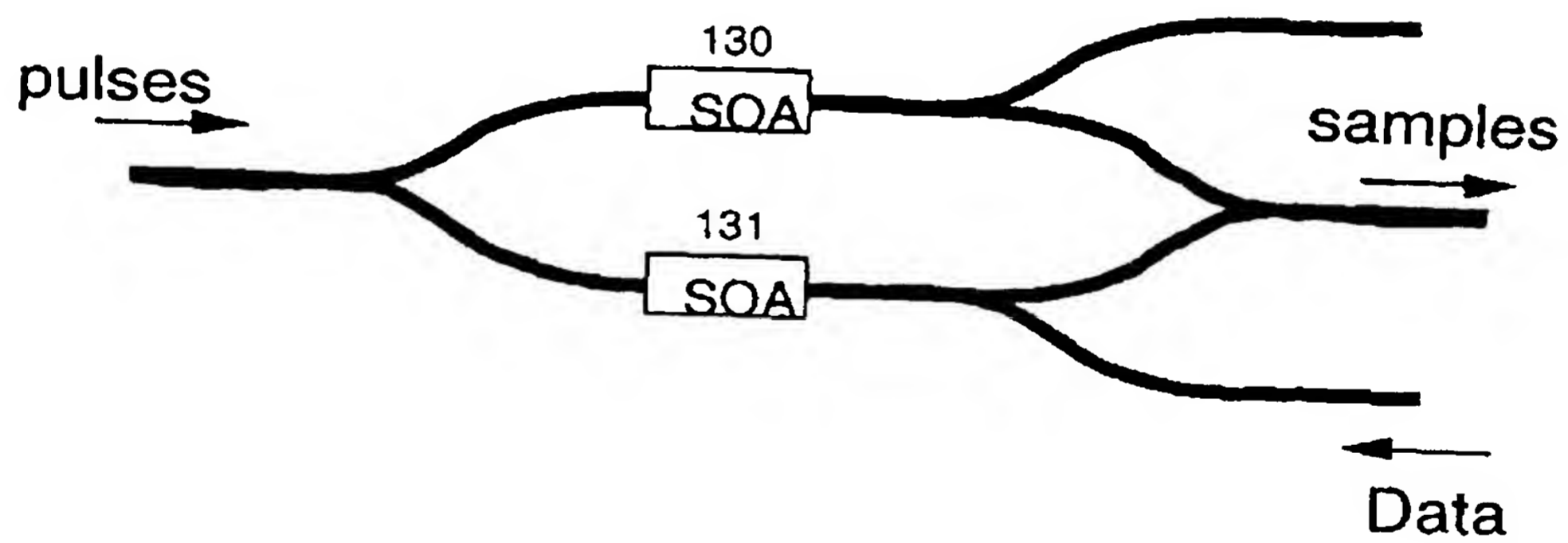


Fig 18 Interferometer Arrangement

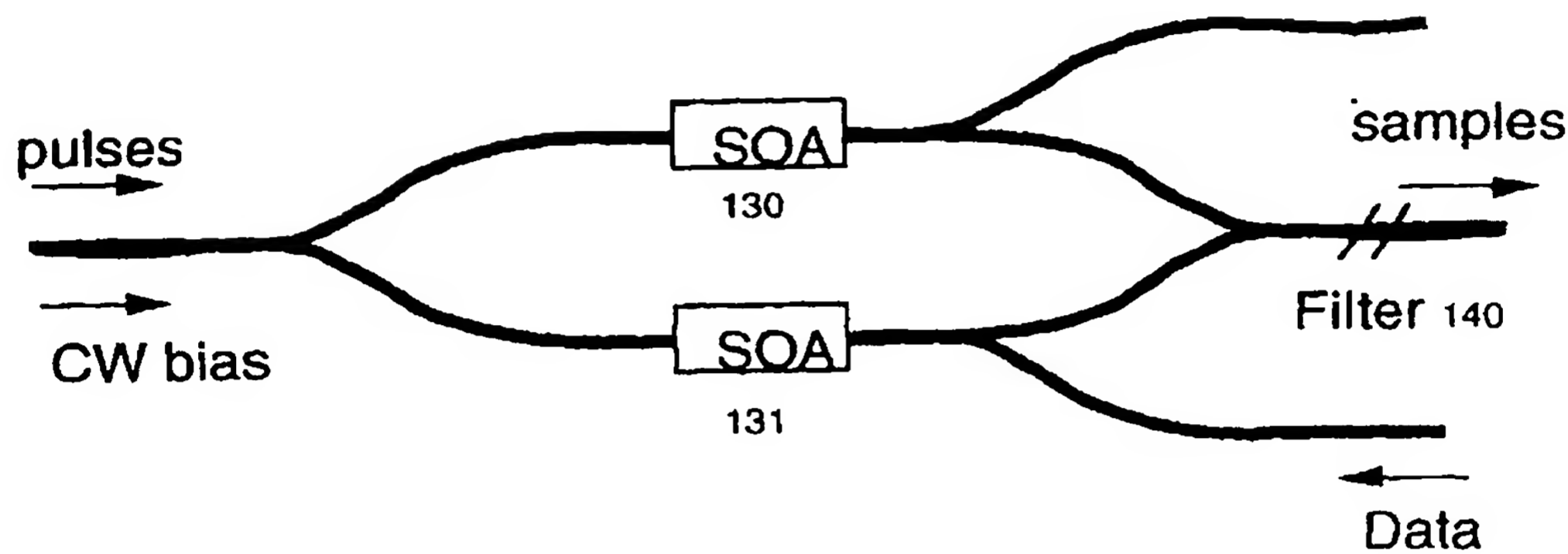


Fig 19 Interferometer Arrangement

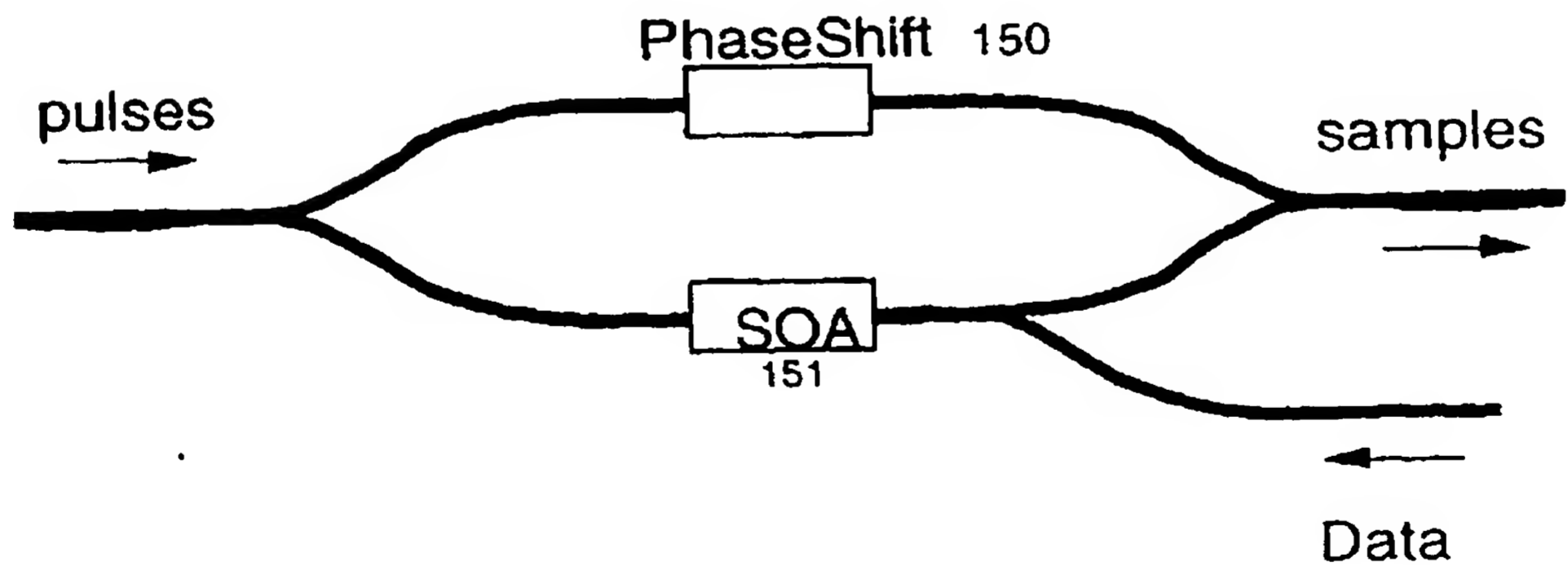


Fig 20 Interferometer Arrangement

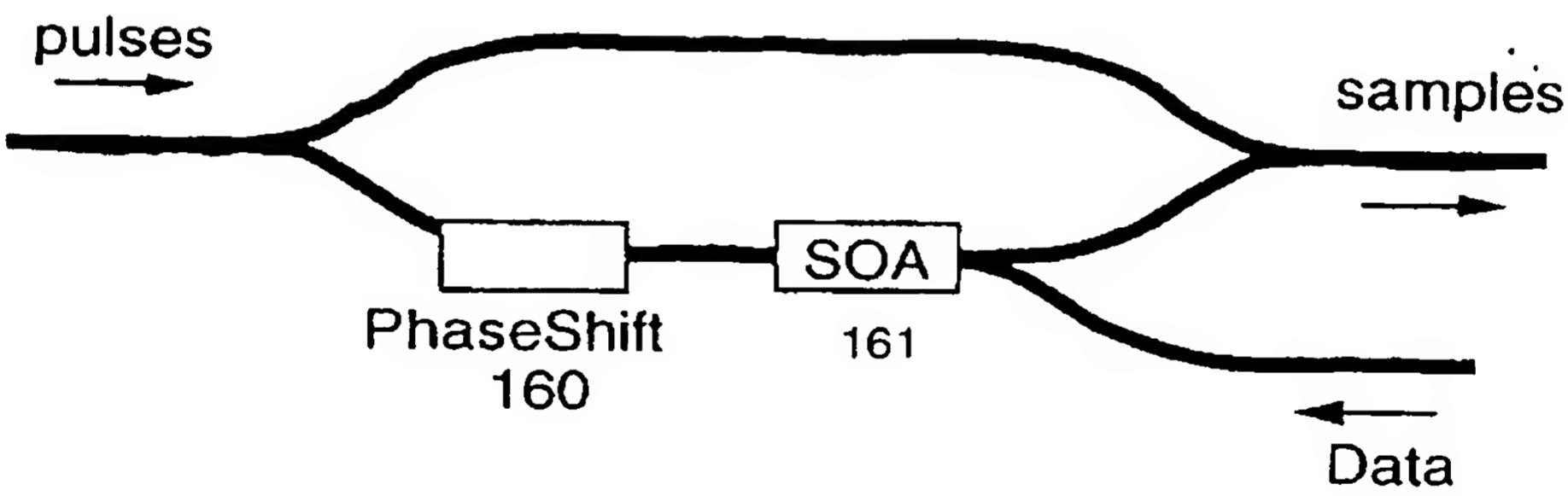
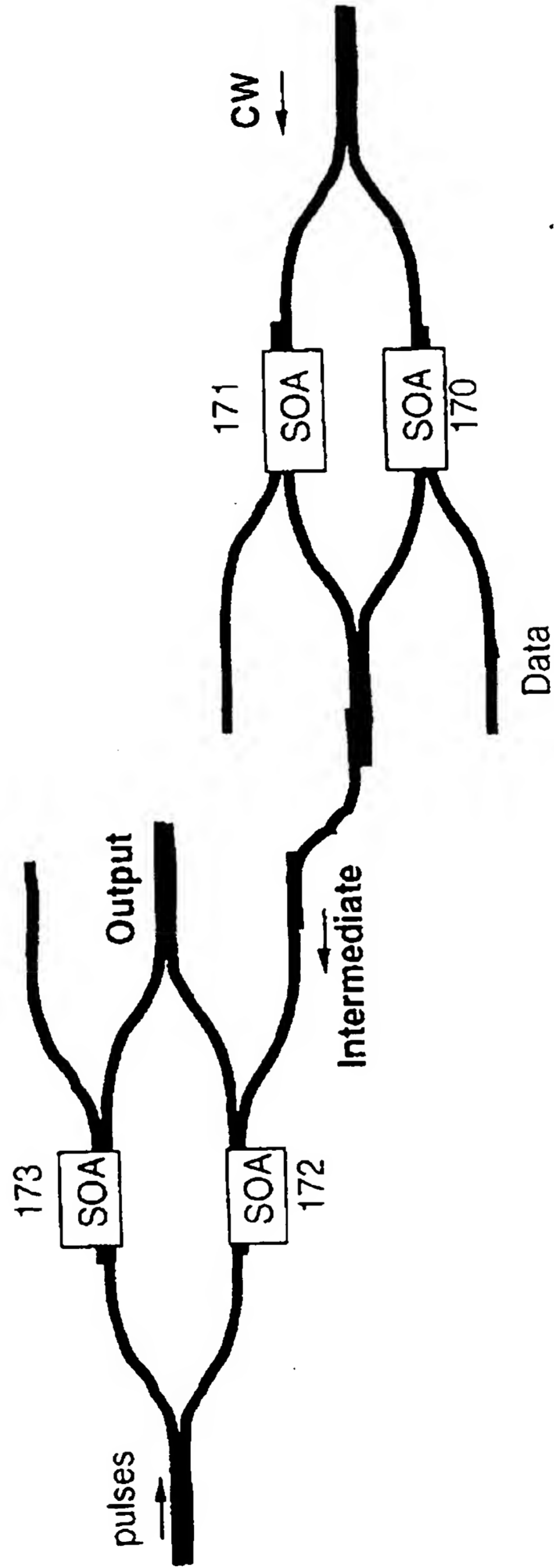


Fig 21 Two stage interferometer arrangement



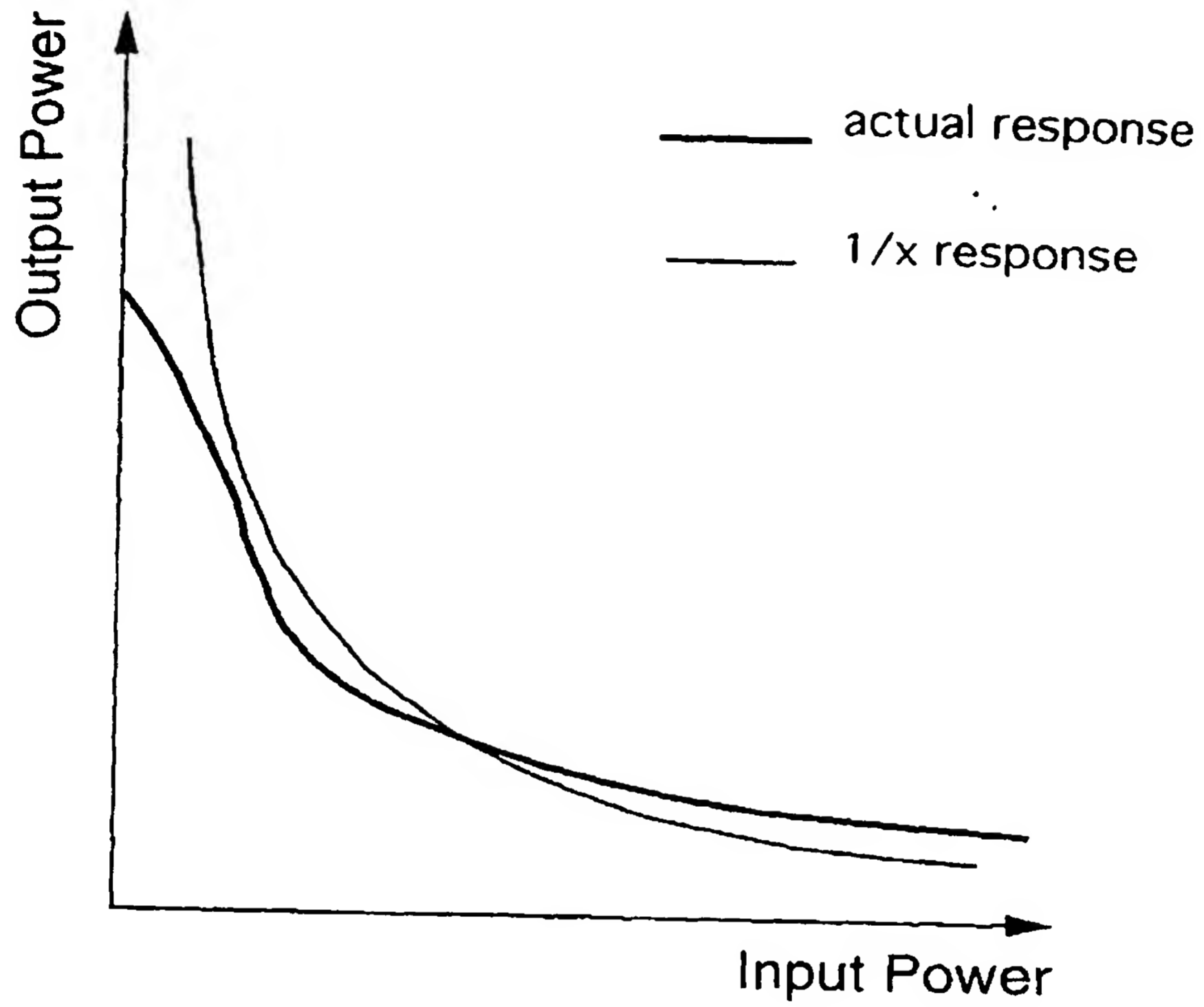
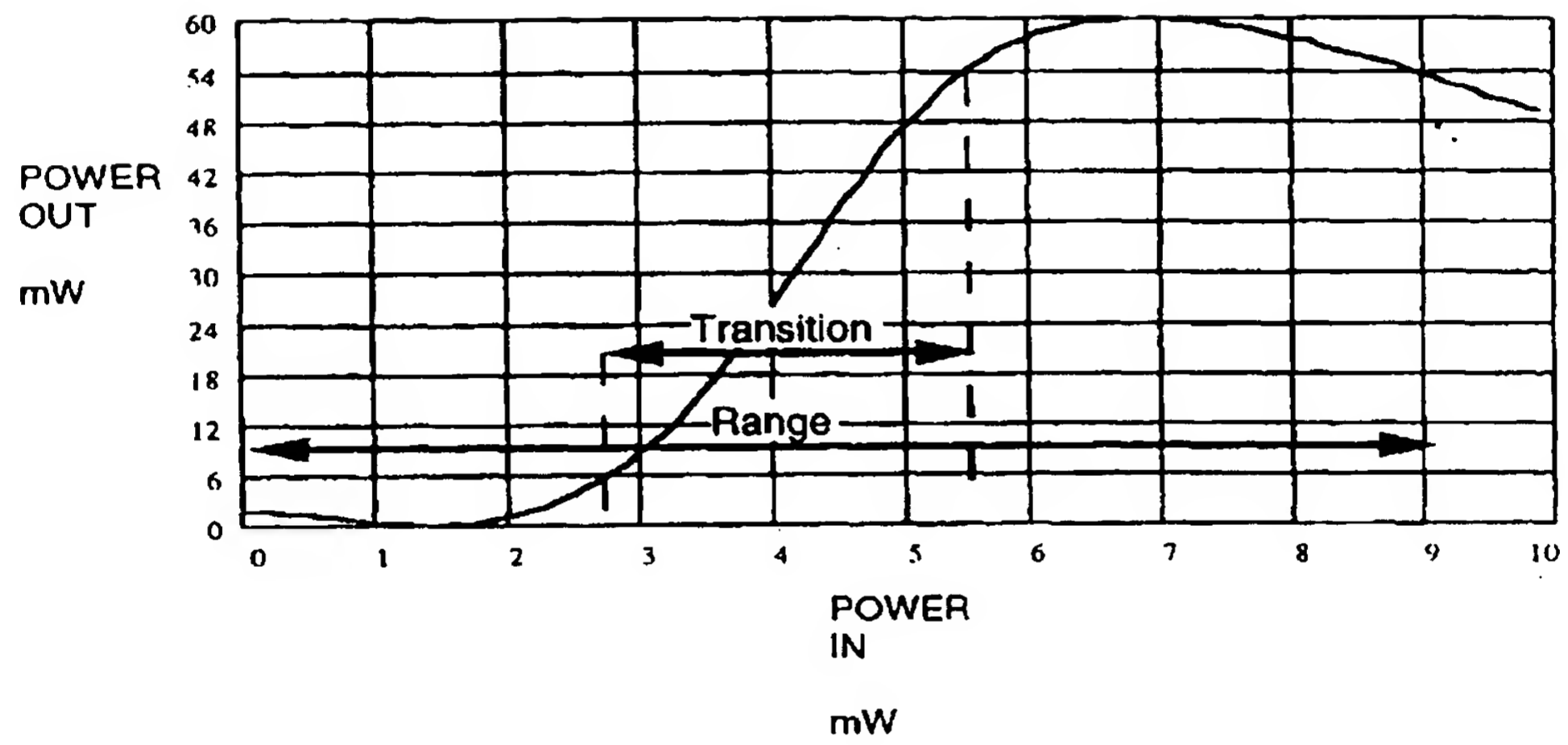
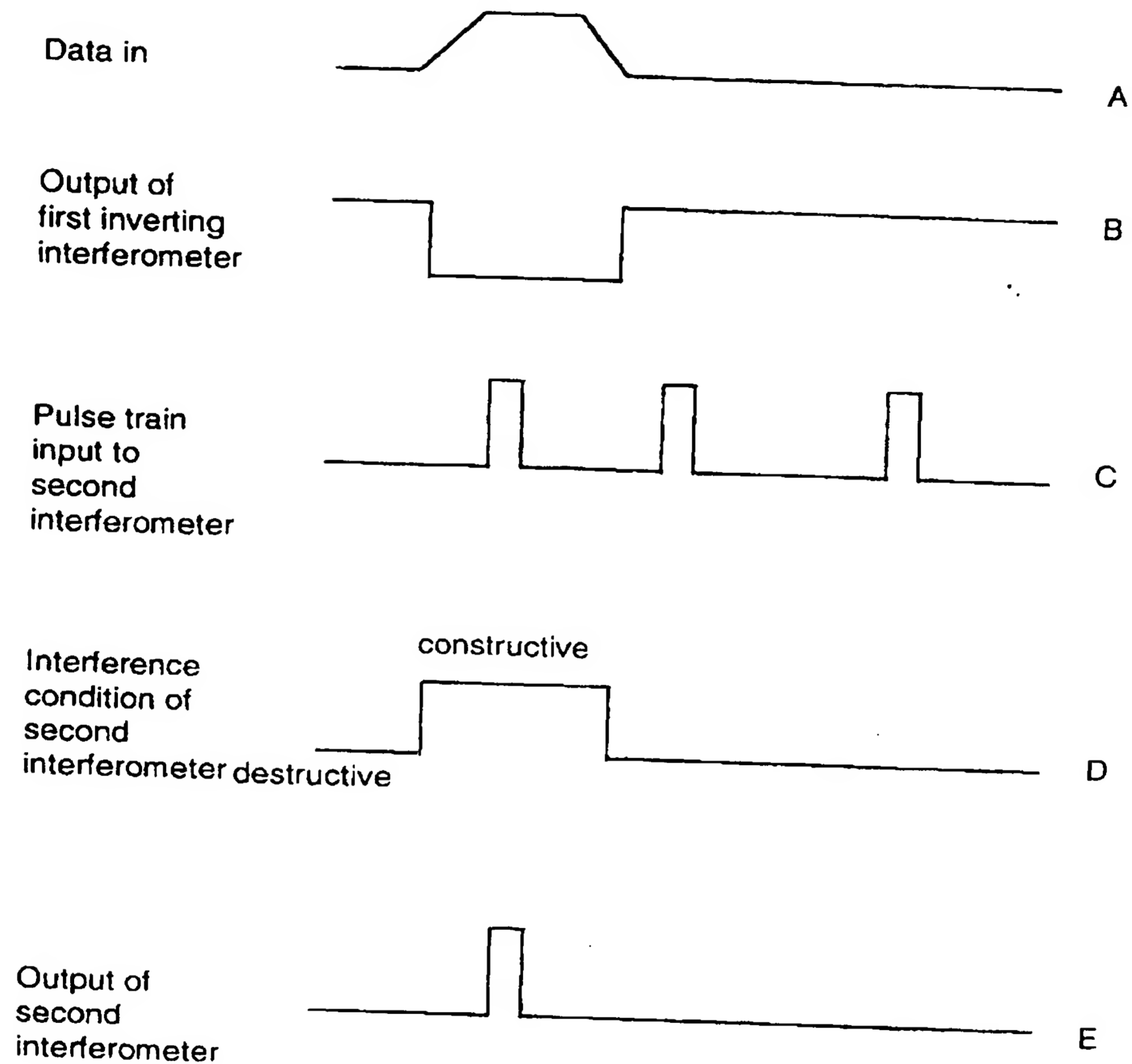


Fig 22  
Single stage non-linear  
inverting response compared  
to 1/x response



**Fig 23** overall response



**Fig 24**  
**OPERATION OF TWO STAGE**  
**INTERFOMETER ARRANGEMENT**



Europäisches Patentamt  
European Patent Office  
Office européen des brevets



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H04B 10/17, H04L 7/00**

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24.06.1998 Bulletin 1998/26

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(72) Inventors:  
• **Roberts, Kim Byron**  
**Welwyn Garden City, Herts AL8 7DL (GB)**  
• **Hadjifotiou, Anagnostis**  
**Harlow, Essex CM19 4RD (GB)**

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**29.05.1997 US 865492**

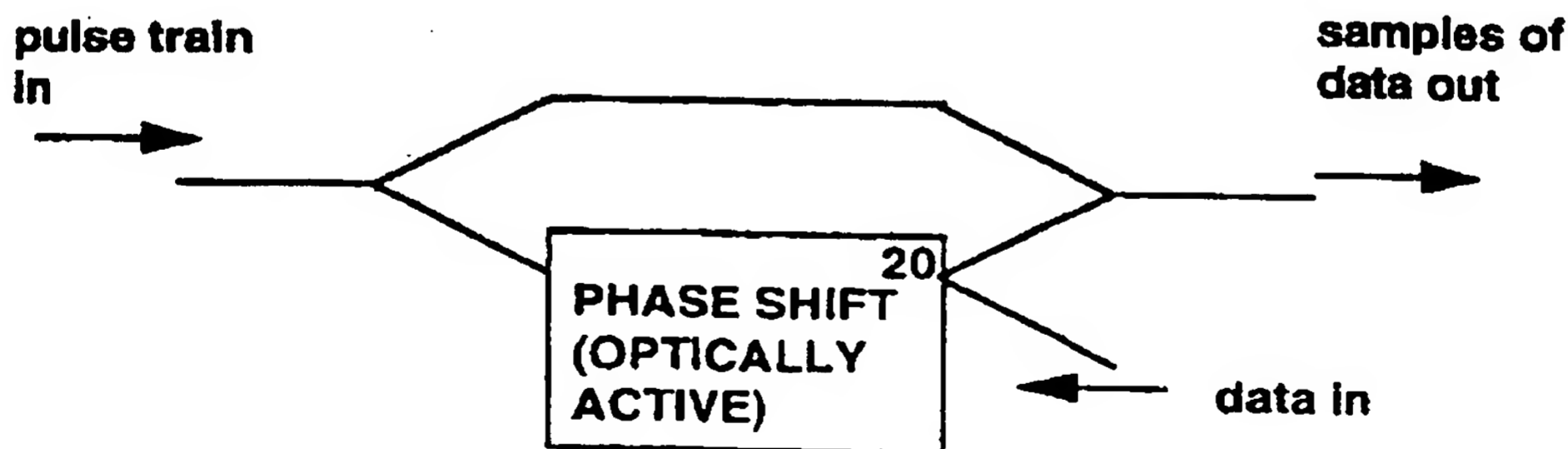
(74) Representative: **Ryan, John Peter William et al**  
**Nortel Networks**  
**Intellectual Property Law Group**  
**London Road**  
**Harlow, Essex CM17 9NA (GB)**

(71) Applicant: **NORTEL NETWORKS CORPORATION**  
**Montreal, Quebec H2Y 3Y4 (CA)**

(54) **All-optical sampling by modulating a pulse train**

(57) An interferometer, such as a Mach-Zehnder type is fed with a pulse train. One arm is fed with a data stream, so as to modulate the pulse train according to the data stream. This enables the data stream to be re-generated, or sampled without converting from optical

form into electrical form. Thus all optical regeneration, multiplexing, demultiplexing or retiming to remove jitter, can be achieved. An optical amplifier (20) in one arm of the interferometer enables the interference condition of the interferometer to be varied, to cause the pulse train to be modulated by the data.



**Fig 3**  
**INTERFEROMETER ARRANGEMENT**



European Patent  
Office

# EUROPEAN SEARCH REPORT

Application Number  
EP 97 30 9354

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
X,D	AGRAWAL N ET AL: "Optical signal processing using monolithically integrated semiconductor laser amplifier structures" OSA TRENDS IN OPTICS AND PHOTONICS (OSA TOPS) VOL.5 - OPTICAL AMPLIFIERS AND THEIR APPLICATIONS - FROM THE TOPICAL MEETING, MONTEREY, CA, USA, 11-13 JULY 1996, pages 205-220, XP002084133 ISBN 1-55752-435-X, 1996, Washington, DC, USA, Opt. Soc. America, USA * figure 2 of page 210 * * figures of pages 217,218 *	1,16-19	G02F1/35 G02F2/00 H04B10/17 H04L7/00
A	---	2,8-11	
A	JOERGENSEN C ET AL: "Wavelength conversion by optimized monolithic integrated Mach-Zehnder interferometer" IEEE PHOTONICS TECHNOLOGY LETTERS, APRIL 1996, IEEE, USA, ISSN 1041-1135, vol. 8, no. 4, pages 521-523, XP000587013 * abstract; sections I,II; figure 1 *	1	
A	MIKKELSEN B ET AL: "Polarisation insensitive wavelength conversion of 10 Gbit/s signals with SOAs in a Michelson interferometer" ELECTRONICS LETTERS, 3 FEB. 1994, UK, ISSN 0013-5194, vol. 30, no. 3, pages 260-261, XP000431304 * abstract; figure 1 * --- -/--	1	TECHNICAL FIELDS SEARCHED (Int.Cl.6) G02F H04L H04B
The present search report has been drawn up for all claims			
Place of search <b>THE HAGUE</b>		Date of completion of the search <b>31 May 1999</b>	Examiner <b>Ribbe, A</b>
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

EPO FORM 1503 03/92 (P04C01)



European Patent  
Office

Application Number  
EP 97 30 9354

**CLAIMS INCURRING FEES**

The present European patent application comprised at the time of filing more than ten claims.

- ☐ Only part of the claims have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims and for those claims for which claims fees have been paid, namely claim(s):
- ☐ No claims fees have been paid within the prescribed time limit. The present European search report has been drawn up for the first ten claims.

**LACK OF UNITY OF INVENTION**

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

see sheet B

- ☒ All further search fees have been paid within the fixed time limit. The present European search report has been drawn up for all claims.
- ☐ As all searchable claims could be searched without effort justifying an additional fee, the Search Division did not invite payment of any additional fee.
- ☐ Only part of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the inventions in respect of which search fees have been paid, namely claims:
- ☐ None of the further search fees have been paid within the fixed time limit. The present European search report has been drawn up for those parts of the European patent application which relate to the invention first mentioned in the claims, namely claims:



European Patent  
Office

# EUROPEAN SEARCH REPORT

Application Number

EP 97 30 9354

DOCUMENTS CONSIDERED TO BE RELEVANT				
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)	
A	JINNO M: "All optical signal regularizing/regeneration using a nonlinear fiber Sagnac interferometer switch with signal-clock walk-off" JOURNAL OF LIGHTWAVE TECHNOLOGY, SEPT. 1994, USA, ISSN 0733-8724, vol. 12, no. 9, pages 1648-1659, XP000484344 * abstract; section I; figures 1,10,14 *	5-12		
X	MIKKELSEN B ET AL: "Wavelength conversion devices" OPTICAL FIBER COMMUNICATION (OFC) 1996, SAN JOSE, FEB. 25 - MAR. 1, 1996, PAPER WG1, vol. 2, no. CONG. 19, 25 February 1996, pages 121-122, XP002101384 OPTICAL SOCIETY OF AMERICA * figure 1B *	13-15, 23-26		
X	WO 96 22562 A (BRITISH TELECOMM ET AL) 25 July 1996 * page 2, line 32 - line 35 *	13-15, 23-26		TECHNICAL FIELDS SEARCHED (Int.Cl.6)
A	* page 6, line 30 - page 8, line 36; figure 3 *	29		
P,X	RATOVELOMANANA F ET AL: "Regeneration improvement in all-optical wavelength converter, based on a Mach-Zehnder interferometer, by means of phase-shifter section" ELECTRONICS LETTERS, 11 SEPT. 1997, IEE, UK, ISSN 0013-5194, vol. 33, no. 19, pages 1629-1630, XP000739626 * the whole document *	13-15, 23-26		
-/--				
The present search report has been drawn up for all claims				
Place of search <b>THE HAGUE</b>		Date of completion of the search <b>31 May 1999</b>	Examiner <b>Ribbe, A</b>	
<p><b>CATEGORY OF CITED DOCUMENTS</b></p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent documents, but published on, or after the filing date O : document cited in the application L : document cited for other reasons &amp; : member of the same patent family, corresponding document</p>				

EPO Form 1603 03 92 (P.O. 0001)

European Patent  
OfficeLACK OF UNITY OF INVENTION  
SHEET BApplication Number  
EP 97 30 9354

The Search Division considers that the present European patent application does not comply with the requirements of unity of invention and relates to several inventions or groups of inventions, namely:

## 1. Claims: 1-12,16-22

Method for all-optical modulation of an optical pulse train comprising the steps of:

- inputting the pulse train to a non-loop interferometer;
- inputting an optical data stream to the interferometer, thereby obtaining at the output (i) the pulse train modulated by the data, or -- seen otherwise -- (ii) the data stream sampled by the input pulses (fig. 3,4).

Application to all-optical clock recovery (fig. 5,6; 8,9), regeneration (fig. 11), time division multiplexing and demultiplexing of optical signals (fig. 13-17).

## 2. Claims: 13-15,23-28

An interferometer comprising:

- an input for an optical signal;
- an input for a control signal;
- all-optical means (151;161) for optically altering an interference condition of said optical signal according to the control signal;

wherein the interferometer further comprises:

- "passive", e.g. electro-optical, means (150;160) for still altering said interference condition (fig. 19;20).

Application to all-optical regeneration.

## 3. Claims: 29-32

An optical pulse reshaping arrangement for reshaping an input data signal, comprising:

- two non-linear stages, arranged either in series or in parallel, wherein
- the first stage has a limiting action on the input data signal when the same is at a first logic state, and
- the second stage has a limiting action on the input data signal when the same is at a second logic state (fig.21,24).



European Patent  
Office

# EUROPEAN SEARCH REPORT

Application Number  
EP 97 30 9354

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (InCLs)
A	SIMON J C ET AL: "TWO-STAGE WAVELENGTH CONVERTER WITH IMPROVED EXTINCTION RATIO" OPTICAL FIBER COMMUNICATION. SUMMARIES OF PAPERS PRESENTED AT THE CONFERENCE OFC '95, SAN DIEGO, FEB. 26 - MAR. 3, 1995, 1 January 1995, pages 381-384, XP000653653 INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS * page 381, paragraph 1 * * page 382 * * figure 1 *	29, 30, 32	
A	US 3 724 926 A (LEE T) 3 April 1973 * abstract * * figures 1,2 *	29, 30	
A	SILBERBERG Y: "NON-LINEAR ALL-OPTICAL REGENERATORS" CONFERENCE ON LASERS AND ELECTRO-OPTICS, 9 - 13 June 1986, XP002104403 * the whole document *	29, 30	
			TECHNICAL FIELDS SEARCHED (InCLs)
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 31 May 1999	Examiner Ribbe, A
<p><b>CATEGORY OF CITED DOCUMENTS</b></p> <p>X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document</p> <p>T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons &amp; : member of the same patent family, corresponding document</p>			

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